

17:42:56

## OCA PAD INITIATION - PROJECT HEADER INFORMATION

09/06/88

Active

Project #: E-16-A09  
Center #: R6575-0A0Cost share #: E-16-331  
Center shr #: F6575-0A0Rev #: 0  
OCA file #:  
Work type : RES  
Document : GRANT  
Contract entity: GTRCContract#: DE-FG22-88PC88918  
Prime #:

Mod #:

Subprojects ? : N  
Main project #:Project unit: AE  
Project director(s):  
ZINN B T AE

Unit code: 02.010.110

Sponsor/division names: US DEPT OF ENERGY  
Sponsor/division codes: 141/ DOE PITTSBURGH - PA  
/ 005

Award period: 880901 to 900831 (performance) 901130 (reports)

Sponsor amount	New this change	Total to date
Contract value	139,993.00	139,993.00
Funded	139,993.00	139,993.00
Cost sharing amount		6,976.00

Does subcontracting plan apply ? : N

Title: REDUCTION OF NOX AND SO2 EMISSIONS FROM COAL BURNING PULSE COMBUSTORS



## PROJECT ADMINISTRATION DATA

OCA contact: E. Faith Gleason

894-4820

Sponsor technical contact

Sponsor issuing office

SAYEED AKHTAR, MS922-H  
(412)892-6006  
US DEPT OF ENERGY, PITTSBURGH ENERGY  
TECHNOLOGY CENTER, PO BOX 10940  
PITTSBURGH, PA 15236DAVID L. SCHWARTZ  
(412)892-6597  
PITTSBURGH ENERGY TECHNOLOGY CENTER  
PO BOX 10940, MS 921-165  
PITTSBURGH, PA 15236

Security class (U,C,S,TS) : U

ONR resident rep. is ACO (Y/N): N

Defense priority rating : N/A

GOVT supplemental sheet

Equipment title vests with: Sponsor

GIT X

DOE MAY TRANSFER TITLE OF ANY ITEM WITH UNIT ACQUISITION COST OF \$1K OR MORE.

Administrative comments -

INITIATION. AWARDS \$139, 993 FOR A TWO YEAR GRANT PERIOD, EFFECTIVE 9/1/88.

GEORGIA INSTITUTE OF TECHNOLOGY  
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/06/91

Project No. E-16-A09 \_\_\_\_\_ Center No. R6575-OA0 \_\_\_\_\_

Project Director ZINN B T \_\_\_\_\_ School/Lab AERO ENGR \_\_\_\_\_

Sponsor US DEPT OF ENERGY/DOE PITTSBURGH - PA \_\_\_\_\_

Contract/Grant No. DE-FG22-88PC88918 \_\_\_\_\_ Contract Entity GTRC

Prime Contract No. \_\_\_\_\_

Title REDUCTION OF NOX AND SO2 EMISSIONS FROM COAL BURNING PULSE COMBUSTORS \_\_\_\_\_

Effective Completion Date 900930 (Performance) 901231 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	_____
Final Report of Inventions and/or Subcontracts	Y	_____
Government Property Inventory & Related Certificate	Y	_____
Classified Material Certificate	N	_____
Release and Assignment	Y	_____
Other _____	N	_____
Comments _____		

Subproject Under Main Project No. \_\_\_\_\_

Continues Project No. \_\_\_\_\_

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Management	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

NOTE: Final Patent Questionnaire sent to PDPI.

U. S. DEPARTMENT OF ENERGY  
NOTICE OF ENERGY RD&D PROJECT

1. Descriptive TITLE of work  
(150 characters including spaces)

Reduction of NO<sub>x</sub> and SO<sub>2</sub> Emissions from Coal Burning Pulse Combustors

2. ~~CONTRACT~~ or  
grant number DE-FG22-88PC88918

- 2A. MASTER contract number  
(GOCO's) \_\_\_\_\_

- 2B. Responsible PATENT office Chicago

3. Performing organization CONTROL  
number (internal) E-16-A09

- 3A. Budget and Reporting code AA1525050

- 3B. Funding YEAR for this award  
1989

4. Original contract start date 9-1-88

- 4A. Current contract start date 9-1-88

- 4B. Current contract close date 8-31-90

- 4C. Anticipated project termination  
date \_\_\_\_\_

5. Work STATUS

☐ Proposed ☐ Renewal  
☒ New ☐ Terminated

- 5A. Manpower (FTE) \_\_\_\_\_

- 5B. CONGRESSIONAL district 5th

- 5C. STATE or Country where work is being  
performed Georgia

- 5D. COUNTRY sponsoring research \_\_\_\_\_

6. Name of PERFORMING organization Georgia Tech Research Institute

- 6A. DEPARTMENT or DIVISION  
School of Aerospace  
Engineering

- 6B. Street Address  
225 North Avenue

- 6C. City, State, Zip Code  
Atlanta, GA 30332

7. Circle only one code for TYPE of Organization Performing R&D:

☒ CU - College, university, or trade school  
FF - Federally funded RD&D centers or laboratory operated for an agency of the U. S.  
Government  
IN - Private industry  
NP - Foundation or laboratory not operated for profit  
ST - Regional, state or local government facility  
TA - Trade or professional organization  
US - Federal agency  
XX - Other  
EG - Electric or gas utility

- 8A. Contractor's PRINCIPAL INVESTIGATOR/s or project manager  
Name/s (Last, First, MI) Zinn, Ben T., Powell, Eugene A.

- 8B. PHONE/s (in order of PI names with commercial followed by FTS)

Comm. (404) 894-3033 ; FTS \_\_\_\_\_ ; Comm. (404) 894-3011 ; FTS \_\_\_\_\_

- 8C. PI/s address (if different from that of Performing Organization)

\_\_\_\_\_  
\_\_\_\_\_

9. DOE SUPPORTING Organization (DOE Assistant Secretary and office sponsoring the work; technical monitor; and administrative monitor).

9A. PROGRAM division or office

(full name) Pittsburg Energy Technology Center

Program Office Code \_\_\_\_\_

9B. TECHNICAL monitor (Last, First, MI) Akhtar, Sayeed

9C. Address U.S. Dept. of Energy, Pittsburg  
Energy Technology Center, P. O. Box 10940  
Pittsburgh, PA 15236

9D. Phone \_\_\_\_\_

Comm. (412) 892-6006

FTS \_\_\_\_\_

9E. ADMINISTRATIVE monitor (Last, First, MI) Schwartz, David L.

10. FUNDING in thousands of dollars (K\$). Funds represent budget obligations for operating and capital equipment (FY runs October 1 – September 30).

Funding organization(s)	Current FY <u>89</u>	Next FY <u>90</u>
A. DOE	70.5	69.5
B. Georgia Tech	3.5	3.4
C.		

10D. Does the current FUNDING cover more than one year's work?

Yes X

No \_\_\_\_\_

E. If yes, provide dates (from when to when). 9/1/88 - 8/31/90

11. Descriptive SUMMARY of work. Enter a Project Summary using complete sentences limited to 200 words covering the following: Objective(s), state project objectives quantifying where possible (e.g., "The project objective is to demonstrate 95% recovery of sulphur from raw gas with molten salt recycling at a rate of one gallon per minute."); approach, describe the technical approach used (how the work is to be done); expected product/results, describe the final products or results expected from the project and their importance and relevance.

This research project is based on earlier work done at Georgia Tech which demonstrated that unpulverized coals, both bituminous and subbituminous, can be burned with efficiencies greater than 97% in Rijke type pulse combustors with only 10% excess air. In Rijke combustors the coal is burned in a bed where the presence of acoustic velocity oscillations results in bed fluidization and the intensification in the rates of mass, momentum, and heat transfer processes; phenomena which are apparently responsible for the superior performance of the pulse combustor. The objective of this project is to determine if the nitrogen oxides and sulfur dioxide emissions can be reduced by staging the combustion process and by adding limestone or dolomite to the acoustically fluidized bed or to the flow of combustion gases above the bed. The investigation will determine the dependence of the NO<sub>x</sub> formation upon the total, primary and secondary air flow rates, the location of the primary and secondary combustion regions, and the directions of the injected secondary air flow streams. The dependence of SO<sub>2</sub> formation upon the Ca/S mole ratio, the bed temperature, and the amount of excess air will also be determined. These results will determine if the pulse combustor can be made to meet the federal New Source Performance Standards for NO<sub>x</sub> and SO<sub>2</sub> emissions from industrial boilers.

12. PUBLICATIONS available to the public. List the five most descriptive publications that have resulted from this project in the last year that are available to the public. (Include author, title, where published, year of publication, and any other information you have to complete full bibliographic citation.) Use the back of this form or additional sheets if necessary.

None - New Project

3. KEYWORDS (Listed five terms describing the technical aspects of the project. List specific chemicals and CAS number, if applicable.)

Pulse Combustion  
Nitrogen Oxides  
Sulfur Dioxide  
Coal Combustors  
Combustion Staging

4. RESPONDENT. Name and address of person filling out the Form 538. Give telephone number, including extension (if you have FTS number, please include it) at which person can be reached. Record the date this form was completed or updated. The information in Item 14 will not be published.

Respondent's Name: Eugene A. Powell Phone No.: (404) 894-<sup>3011</sup> Date: 10-11-88  
Street: Georgia Institute of Technology  
School of Aerospace Engineering  
City: Atlanta State: GA Zip: 30332

15. Additional space for furnishing information in items 1 to 14. (Indicate item numbers to which answers apply.)

Item No.

64012482  
RATION 774377  
88.7 1 100  
OFFICE OF CONTRACT

NOTICE: Return this form to the office indicated in the reporting requirements for your award agreement covering this project. If you have completed a similar programmatic office project description during the current Fiscal Year, complete only the new data elements on this form and send it and a copy of the description completed earlier to Department of Energy, Office of Scientific Information, P. O. Box 62, Oak Ridge, TN 37831.

Georgia Institute of Technology  
Lyman Hall/Emerson Building  
Atlanta, Georgia 30332-0259  
404-894-4624; 2629

October 13, 1988

Mr. David L. Schwartz, Contract Specialist  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Schwartz,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period September 1, 1988 through September 30, 1988 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Sayeed Akhtar w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mildred Heyser, OCA/CSD 0420  
File E-16-A09/R6575-OAO✓

# FINANCIAL STATUS REPORT

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED  
U. S. Department of Energy

2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER  
DE-FG22-88PC88918

OMB Approved  
No. 80-R0180

PAGE 1 OF 1

RECIPIENT ORGANIZATION (Name and complete address, including ZIP code)

GEORGIA Tech Research Corporation  
P. O. Box 100117  
Atlanta, GA 30384

4. EMPLOYER IDENTIFICATION NUMBER  
58-0603146

5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NUMBER  
E-16-A09/R6575-OAO

6. FINAL REPORT  
☐ YES ☒ NO

7. BASIS  
☒ CASH ☐ ACCRUAL

8. PROJECT/GRANT PERIOD (See instructions)

FROM (Month, day, year)  
September 1, 1988

TO (Month, day, year)  
August 31, 1990

9. PERIOD COVERED BY THIS REPORT

FROM (Month, day, year)  
September 1, 1988

TO (Month, day, year)  
September 30, 1988

## STATUS OF FUNDS

PROGRAMS/FUNCTIONS/ACTIVITIES ▶	(a)	(b)	(c)	(d)	(e)	(f)	TOTAL (g)
Net outlays previously reported	\$	\$	\$	\$	\$	\$	\$ - 0 -
Total outlays this report period							8,182.61
Less: Program income credits							- 0 -
Net outlays this report period (Line b minus line c)							8,182.61
Net outlays to date (Line a plus line d)							8,182.61
Less: Non-Federal share of outlays							- 0 -
Net Federal share of outlays (Line e minus line f)							8,182.61
Net unliquidated obligations							29,752.54
Less: Non-Federal share of unliquidated obligations shown on line h							3,469.82
Net Federal share of unliquidated obligations							26,282.72
Net Federal share of outlays and unliquidated obligations							34,465.33
Total cumulative amount of Federal funds authorized							139,993.00
obligated balance of Federal funds							\$ 105,527.67

a. TYPE OF RATE (Place "X" in appropriate box)	<input checked="" type="checkbox"/> PROVISIONAL <input type="checkbox"/> PREDETERMINED <input type="checkbox"/> FINAL <input type="checkbox"/> FIXED
b. RATE 60.0%	c. BASE MTDC
d. TOTAL AMOUNT \$3,068.48	e. FEDERAL SHARE \$3,068.48

13. CERTIFICATION  
I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

SIGNATURE OF AUTHORIZED CERTIFYING OFFICIAL  
[Signature]

DATE REPORT SUBMITTED  
October 12, 1988

TYPED OR PRINTED NAME AND TITLE  
David V. Welch, Director  
Grants & Contracts Acctg.

TELEPHONE (Area code, number and extension)  
(404) 894-2629

NOTE: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with existing legislation.  
FY'89 Direct Costs Indirect Costs  
\$5,114.13 @60.0% \$3,068.48

Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629

STANDARD FORM 288 (7-76)  
Prescribed by Office of Management and Budget  
Cir. No. A-110

Georgia Institute of Technology  
Lyman Hall/Emerson Building  
Atlanta, Georgia 30332-0259  
404-894-4624; 2629

January 11, 1989

④ Mr. David L. Schwartz, Contract Specialist  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Schwartz,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period October 1, 1988 through December 31, 1988 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
① Mr. Sayeed Akhtar w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mildred Heyser, OCA/CSD 0420  
File E-16-A09/R6575-OAO✓

# FINANCIAL STATUS REPORT

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED

U. S. Department of Energy

2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER

DE-FC22-88PC88918

OMB Approved  
No. 80-RO180

PAGE OF

1 1 PAGE

RECIPIENT ORGANIZATION (Name and complete address, including ZIP code)

Georgia Tech Research Corporation  
P. O. Box 100117  
Atlanta, GA 30384

4. EMPLOYER IDENTIFICATION NUMBER

58-0603146

5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NUMBER

E-16-A09/R6575-0A0

6. FINAL REPORT

☐ YES ☒ NO

7. BASIS

☒ CASH ☐ ACCRUAL

8. PROJECT/GRANT PERIOD (See instructions)

FROM (Month, day, year)

September 1, 1988

TO (Month, day, year)

August 31, 1990

9. PERIOD COVERED BY THIS REPORT

FROM (Month, day, year)

October 1, 1988

TO (Month, day, year)

December 31, 1988

## STATUS OF FUNDS

PROGRAMS/FUNCTIONS/ACTIVITIES ▶	(a)	(b)	(c)	(d)	(e)	(f)	TOTAL (g)
Net outlays previously reported	\$	\$	\$	\$	\$	\$	\$ 8,182.61
Total outlays this report period							11,678.85
Less: Program income credits							- 0 -
Net outlays this report period (Line b minus line c)							11,678.85
Net outlays to date (Line a plus line d)							19,861.46
Less: Non-Federal share of outlays							1,071.55
Total Federal share of outlays (Line e minus line f)							18,789.91
Total unliquidated obligations							20,500.48
Less: Non-Federal share of unliquidated obligations shown on line h							2,313.22
Federal share of unliquidated obligations							18,187.26
Total Federal share of outlays and unliquidated obligations							36,977.17
Total cumulative amount of Federal funds authorized							139,993.00
Unobligated balance of Federal funds							103,015.83

10. TYPE OF RATE (Place "X" in appropriate box)	<input checked="" type="checkbox"/> PROVISIONAL <input type="checkbox"/> PREDETERMINED <input type="checkbox"/> FINAL <input type="checkbox"/> FIXED		
	11. RATE 60.0%	12. BASE MTDC	13. TOTAL AMOUNT \$4,379.57
			14. FEDERAL SHARE \$3,977.74

15. CERTIFICATION  
I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

SIGNATURE OF AUTHORIZED CERTIFYING OFFICIAL

TYPED OR PRINTED NAME AND TITLE  
David V. Welch, Director  
Grants & Contracts Accounting

DATE REPORT SUBMITTED

January 11, 1989

TELEPHONE (Area code, number and extension)  
(404) 894-2629

16. Attach any explanation deemed necessary or information required by Federal sponsoring agency in compliance with award legislation.  
Georgia Tech Fiscal Year Ends June 30

FY'89	Direct Costs	Indirect Costs
9/1/88 - 9/30/88	\$5,114.13	\$3,068.48
10/1/88 - 12/31/88	6,629.56	3,977.74

Non-Federal	Direct Costs	Indirect Costs
9/1/88- 9/30/88	\$ - 0 -	
10/1/88-12/31/88	669.72	

Non-Federal	Direct Costs	Indirect Costs
9/1/88- 9/30/88	\$ - 0 -	
10/1/88-12/31/88	401.83	

STANDARD FORM 260 (7-76)  
Prescribed by Office of Management and Budget  
Cir. No. A-110

Georgia Institute of Technology

Lyman Hall/Emerson Building

Atlanta, Georgia 30332-0259

404-894-4624; 2629

(404) 894-5519 Fax

April 13, 1989

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period January 1, 1989 through March 31, 1989 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mildred Heyser, OCA/CSD 0420  
File E-16-A09/R6575-0A0

Federal Agency and Organizational Element to Which Report is Submitted  S. Department of Energy		2. Federal Grant or Other Identifying Number Assigned By Federal Agency  DE-FG22-88PC88918		OMB Approval No.  0348-0039	Page  1	of  1 pages
Recipient Organization (Name and complete address, including ZIP code) Georgia Tech Research Corporation P. O. Box 100117 Atlanta, Georgia 30384						
Employer Identification Number  8-0603146		5. Recipient Account Number or Identifying Number  E-16-A09/R6575-0A0		6. Final Report <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		7. Basis <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual
Reporting Period (See instructions) From: (Month, Day, Year) September 1, 1988		To: (Month, Day, Year) August 31, 1990		9. Period Covered by this Report From: (Month, Day, Year) January 1, 1989		To: (Month, Day, Year) March 31, 1989
Transactions:		I Previously Reported		II This Period		III Cumulative
Total outlays		19,861.46		21,026.35		40,887.81
Recipient share of outlays		1,071.55		1,134.14		2,205.69
Federal share of outlays		18,789.91		19,892.21		38,682.12
Total unliquidated obligations						13,523.31
Recipient share of unliquidated obligations						921.60
Federal share of unliquidated obligations						12,601.71
Total Federal share (Sum of lines e and f)						51,283.83
Total Federal funds authorized for this funding period						139,993.00
Unobligated balance of Federal funds (Line h minus line g)						\$ 88,709.17
a. Type of Rate (Place "X" in appropriate box) <input checked="" type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input type="checkbox"/> Fixed						
b. Rate See Below		c. Base MTDC		d. Total Amount \$15,332.93		e. Federal Share \$14,505.60
Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.  Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629  Georgia Tech Fiscal Year Ends June 30						
Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.						
Printed Name and Title Ed V. Welch, Director Office of Grants and Contracts Accounting				Telephone (Area code, number and extension) (404) 894-2629		
Signature of Authorized Certifying Official				Date Report Submitted April 13, 1989		

Portions not Usable \_\_\_\_\_ Direct Costs \_\_\_\_\_ Indirect Costs \_\_\_\_\_

89 @ 60.0%

01/88-12/31/88	\$11,743.69	\$7,046.22
01/89-03/31/89	12,432.63	7,459.58

		Non-Federal	
		Direct Costs	Indirect Cost
09/01/88-12/31/88	\$669.72	\$401.83	
01/01/89-03/31/89	708.84	425.30	

**Georgia Institute of Technology**

Lyman Hall/Emerson Building

Atlanta, Georgia 30332-0259

404-894-4624; 2629

Fax: 404-894-5519

July 20, 1989

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period April 1, 1989 through June 30, 1989 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420 ✓  
File E-16-A09/R6575-OAO

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

Federal Agency and Organizational Element to Which Report is Submitted  U.S. Department of Energy	2. Federal Grant or Other Identifying Number Assigned By Federal Agency  DE-FG22-88PC88918	OMB Approval No. <b>0348-0039</b>	Page 1	of 1 pages
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Recipient Organization (Name and complete address, including ZIP code) Georgia Tech Research Corporation P.O. Box 100117 Atlanta, Ga. 30384
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Employer Identification Number 58-0603146	5. Recipient Account Number or Identifying Number E-16-A09/R6575-0A0	6. Final Report <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	7. Basis <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual
--	---	--	---

Funding/Grant Period (See Instructions) From: (Month, Day, Year) September 1, 1988	To: (Month, Day, Year) August 31, 1990	9. Period Covered by this Report From: (Month, Day, Year) April 1, 1989	To: (Month, Day, Year) June 30, 1989
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Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total outlays	40,887.81	15,829.34	56,717.15
b. Recipient share of outlays	2,205.69	1,130.31	3,336.00
c. Federal share of outlays	38,682.12	14,699.03	53,381.15
d. Total unliquidated obligations			1,406.40
e. Recipient share of unliquidated obligations			- 0 -
f. Federal share of unliquidated obligations			1,406.40
g. Total Federal share (Sum of lines c and f)			54,787.55
h. Total Federal funds authorized for this funding period			139,993.00
i. Unobligated balance of Federal funds (Line h minus line g)			85,205.45

a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input checked="" type="checkbox"/> Final <input type="checkbox"/> Fixed	Indirect Expense
b. Rate 60.0%	c. Base MTDC
d. Total Amount \$21,268.94	e. Federal Share \$20,017.94

Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.

Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629

Georgia Tech Fiscal Year Ends June 30

**Certification:** I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

Name and Title David V. Welch, Director Office of Grants & Contracts Accounting	Telephone (Area code, number and extension) (404) 894-2629
Signature of Authorized Certifying Official 	Date Report Submitted July 20, 1989

Previous Editions not Usable	<u>DIRECT COSTS</u>	<u>INDIRECT COSTS</u>	Standard Form 269A (REV 4-88) Prescribed by OMB Circulars A-102 and A-110	
89 @ 60.0%			<u>NON-FEDERAL</u>	
01/88-03/31/89	\$24,176.32	\$14,505.80	<u>DIRECT COSTS</u>	<u>INDIRECT COSTS</u>
01/89-06/30/89	9,186.89	5,512.14	\$1,378.56	\$827.13
			706.44	423.87

**Georgia Institute of Technology**

Lyman Hall, Emerson Building

Atlanta, Georgia 30332-0259

404-894-4624; 2629

Fax: 404-894-5519

December 14, 1989

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period July 1, 1989 through September 30, 1989 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420 ✓  
File E-16-A09/R6575-0A0

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

<b>1. Federal Agency and Organizational Element to Which Report is Submitted</b>  U. S. Department of Energy		<b>2. Federal Grant or Other Identifying Number Assigned By Federal Agency</b>  DE-FG22-88PC88918		<b>OMB Approval No.</b> 0348-0039	<b>Page</b> 1	<b>of</b> 1 pages
<b>3. Recipient Organization (Name and complete address, including ZIP code)</b> GEORGIA TECH RESEARCH CORPORATION ✓ P. O. BOX 100117 ATLANTA, GEORGIA 30384						
<b>4. Employer Identification Number</b> 58-0603146		<b>5. Recipient Account Number or Identifying Number</b> E-16-A09/R6575-0A0		<b>6. Final Report</b> <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		<b>7. Basis</b> <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual
<b>8. Funding/Grant Period (See Instructions)</b> From: (Month, Day, Year) September 1, 1988		To: (Month, Day, Year) August 31, 1990		<b>9. Period Covered by this Report</b> From: (Month, Day, Year) July 1, 1989		To: (Month, Day, Year) September 30, 1989
<b>10. Transactions:</b>				I Previously Reported	II This Period	III Cumulative
a. Total outlays				56,717.15	18,856.53	75,573.68
b. Recipient share of outlays				3,336.00	-0-	3,336.00
c. Federal share of outlays				53,381.15	18,856.53	72,237.68
d. Total unliquidated obligations						49,142.89
e. Recipient share of unliquidated obligations						3,447.99
f. Federal share of unliquidated obligations						45,694.90
g. Total Federal share (Sum of lines c and f)						117,932.58
h. Total Federal funds authorized for this funding period						139,993.00
i. Unobligated balance of Federal funds (Line h minus line g)						22,060.42
<b>1. Indirect Expense</b>						
a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input checked="" type="checkbox"/> Fixed						
b. Rate FY'89 @ 60.0% FY'90 @ 62.5%		c. Base MTDC		d. Total Amount		e. Federal Share
<b>2. Remarks:</b> Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.  Questions pertaining to this report should be directed to: Geraldine Reese (404) 894-2629  GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30.						
<b>3. Certification:</b> I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.						
Typed or Printed Name and Title David V. Welch, Director Grants and Contracts Accounting					Telephone (Area code, number and extension) (404) 894-2629	
Signature of Authorized Certifying Official					Date Report Submitted December 14, 1989	

Previous Editions not Usable	Direct Costs	Indirect Costs		
89 @ 60.0%	\$ 33,363.21	\$ 20,017.94		
90 @ 62.5%				
01/89 - 09/30/89	11,604.02	7,252.51		
			FY'89	
			Direct Costs	Indirect Costs
			\$ 2,08.00	\$ 1,251.00

Standard Form 269A (REV 4-88)  
 Prescribed by OMB Circulars A-102 and A-110  
**NON - FEDERAL**

Georgia Institute of Technology  
Lyman Hall/Emerson Building  
Atlanta, Georgia 30332-0259  
404-894-4624; 2629

January 12, 1990

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF 269) for Grant No. DE-FG22-88PC88918 covering the period October 1, 1989 through December 31, 1989 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420✓  
File E-16-A09/R6575-0A0

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

<b>1. Federal Agency and Organizational Element to Which Report is Submitted</b>  U. S. Department of Energy		<b>2. Federal Grant or Other Identifying Number Assigned By Federal Agency</b>  DE-FG22-88(C88918)		<b>OMB Approval No.</b>  0348-0039	<b>Page</b>  1	<b>of</b>  1 pages
<b>3. Recipient Organization (Name and complete address, including ZIP code)</b> GEORGIA TECH RESEARCH CORPORATION P. O. BOX 100117 ATLANTA, GA 30384						
<b>4. Employer Identification Number</b>  58-0603146		<b>5. Recipient Account Number or Identifying Number</b>  E-16-A09/R6575-0A0		<b>6. Final Report</b> <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		<b>7. Basis</b> <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual
<b>8. Funding/Grant Period (See Instructions)</b> From: (Month, Day, Year) September 1, 1988		To: (Month, Day, Year) August 31, 1990		<b>9. Period Covered by this Report</b> From: (Month, Day, Year) October 1, 1989		To: (Month, Day, Year) December 31, 1989
<b>10. Transactions:</b>				I Previously Reported	II This Period	III Cumulative
a. Total outlays				75,573.68	19,021.00	94,594.68
b. Recipient share of outlays				3,336.00	1,052.74	4,388.74
c. Federal share of outlays				72,237.68	17,968.26	90,205.94
d. Total unliquidated obligations						33,385.14
e. Recipient share of unliquidated obligations						1,828.13
f. Federal share of unliquidated obligations						31,557.01
g. Total Federal share (Sum of lines c and f)						121,762.95
h. Total Federal funds authorized for this funding period						139,993.00
i. Unobligated balance of Federal funds (Line h minus line g)						18,230.05
<b>11. Indirect Expense</b>						
a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input checked="" type="checkbox"/> Fixed						
b. Rate		c. Base		d. Total Amount		e. Federal Share
See Attached		MTDC		7,317.77		6,912.87
<b>12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.</b>  <div style="display: flex; justify-content: space-between;"> <div>           GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30.         </div> <div>           Questions pertaining to this report should be directed to:            Geraldine Reese (404) 894-2629         </div> </div>						
<b>13. Certification:</b> I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.						
Typed or Printed Name and Title David V. Welch, Director Office of Grants and Contracts Accounting					Telephone (Area code, number and extension)  (404) 894-2629	
Signature of Authorized Certifying Official					Date Report Submitted  January 12, 1990	

Attachment

01/12/90

DOE Grant # DE-FG22-88PC88918

	<u>Direct Costs</u>	<u>Indirect Costs</u>
FY'89 @ 60.0%	\$ 33,363.21	\$ 20,017.94
FY'90 @ 62.5%	22,659.41	14,165.38

Report Period

	<u>Direct Costs</u>	<u>Indirect Costs</u>
10/01/89 - 12/31/89 @ 62.5%	\$ 11,055.39	\$ 6,912.87 <sup>(1)</sup>

NON-FEDERAL

FY'89 @ 60.0%	\$ 2,085.00	\$ 1,251.00
FY'90 @ 62.5%	647.84	404.90
10/01/89 - 12/31/89		

(1)

Includes an adjustment of \$3.25 for FY'89 processed in FY'90.

# Georgia Tech

Office of Grants and Contracts Accounting

**Georgia Institute of Technology**

Hinman Building

Atlanta, Georgia 30332-0259

404-894-4624; 2629

Fax: 404-894-5519

April 20, 1990

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF-269) for Grant No. DE-FG22-88PC88918 covering the period January 1, 1990 through March 31, 1990 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420✓  
File E-16-A09/R6575-0A0

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

<b>1. Federal Agency and Organizational Element to Which Report is Submitted</b>  U. S. Department of Energy		<b>2. Federal Grant or Other Identifying Number Assigned By Federal Agency</b>  DE-FG22-88PC88918		<b>OMB Approval No.</b> 0348-0039	<b>Page</b> 1	<b>of</b> 1 pages
<b>3. Recipient Organization (Name and complete address, including ZIP code)</b>  GEORGIA TECH RESEARCH CORPORATION P. O. BOX 100117 ATLANTA, GA 30384						
<b>4. Employer Identification Number</b>  58-0603146		<b>5. Recipient Account Number or Identifying Number</b>  E-16-A09/R6575-0A0		<b>6. Final Report</b> <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		<b>7. Basis</b> <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Actual
<b>8. Funding/Grant Period (See Instructions)</b> From: (Month, Day, Year) September 01, 1988		To: (Month, Day, Year) August 31, 1990		<b>9. Period Covered by this Report</b> From: (Month, Day, Year) January 01, 1990		To: (Month, Day, Year) March 31, 1990
<b>10. Transactions:</b>				I Previously Reported	II This Period	III Cumulative
a. Total outlays				94,594.68	16,832.08	111,426.76
b. Recipient share of outlays				4,388.74	1,114.16	5,502.90
c. Federal share of outlays				90,205.94	15,717.92	105,923.86
d. Total unliquidated obligations						15,153.24
e. Recipient share of unliquidated obligations						926.25
f. Federal share of unliquidated obligations						14,226.99
g. Total Federal share (Sum of lines c and f)						120,150.85
h. Total Federal funds authorized for this funding period						139,993.00
i. Unobligated balance of Federal funds (Line h minus line g)						19,842.15
<b>11. Indirect Expense</b>						
a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input checked="" type="checkbox"/> Fixed						
b. Rate		c. Base		d. Total Amount		e. Federal Share
SEE ATTACHED		MTDC		\$6,473.87		\$6,045.35
<b>12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.</b>  <div style="text-align: center;">             QUESTIONS PERTAINING TO THIS REPORT              SHOULD BE DIRECTED TO:               GEORGIA TECH FISCAL YEAR ENDS JUNE 30      GERALDINE REESE (404) 894-2629           </div>						
<b>13. Certification:</b> I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.						
Typed or Printed Name and Title  David V. Welch, Director, Grants & Contracts Accounting				Telephone (Area code, number and extension)  (404) 894-2629		
Signature of Authorized Certifying Official  				Date Report Submitted  April 18, 1990		

Attachment  
 04/18/90  
 Financial Status Report  
 Grant #DE-FG22-88PC88918  
 Period Covered: 01/01/90 - 03/31/90

	<u>Direct Costs</u>	<u>Indirect Costs</u>
FY'89 @ 60.0%	\$33,363.21	\$20,017.94
FY'90 @ 62.5%	32,331.98	20,210.73

REPORT PERIOD

	<u>Direct Costs</u>	<u>Indirect Costs</u>
01/01/90 - 03/31/90 @ 62.5%	\$9,672.57	\$6,045.35

NON-FEDERAL

FY'89 @ 60.0%	\$2,085.00	\$1,251.00
FY'90 @ 62.5%		
10/01/89 - 12/31/89	647.84	404.90
01/01/90 - 03/31/90	685.64	428.52

**Georgia Institute of Technology**

Hinman Building  
Atlanta, Georgia 30332-0259  
404-894-4624: 2629  
Fax: 404-894-5519

July 18, 1990

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF-269) for Grant No. DE-FG22-88PC88918 covering the period April 1, 1990 through June 30, 1990 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420 ✓  
File E-16-A09/R6575-0A0

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted  U. S. Department of Energy	2. Federal Grant or Other Identifying Number Assigned By Federal Agency  DE-FG22-88PC88918	OMB Approval No.  0348-0039	Page  1	of  1 pages
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3. Recipient Organization (Name and complete address, including ZIP code)  GEORGIA TECH RESEARCH CORPORATION P. O. BOX 100117 ATLANTA, GA 30384
---

4. Employer Identification Number  58-0603146	5. Recipient Account Number or Identifying Number  E-16-A09/R6575-0A0	6. Final Report <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	7. Basis <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual
---	---	--	---

8. Funding/Grant Period (See Instructions) From: (Month, Day, Year) September 01, 1988	To: (Month, Day, Year) August 31, 1990	9. Period Covered by this Report From: (Month, Day, Year) April 01, 1990	To: (Month, Day, Year) June 30, 1990
---	---	---	---

10. Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total outlays	\$111,426.76	\$26,487.22	\$137,913.98
b. Recipient share of outlays	5,502.90	1,145.15	6,648.05
c. Federal share of outlays	\$105,293.86	25,342.07	131,265.93
d. Total unliquidated obligations			15.57
e. Recipient share of unliquidated obligations			-0-
f. Federal share of unliquidated obligations			15.57
g. Total Federal share (Sum of lines c and f)			131,281.50
h. Total Federal funds authorized for this funding period			139,993.00
i. Unobligated balance of Federal funds (Line h minus line g)			8,711.50

Indirect Expense	a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Prorated <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input checked="" type="checkbox"/> Fixed			
	b. Rate See Attached	c. Base MTDC	d. Total Amount \$10,187.40	e. Federal Share \$9,746.95

Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.

Questions pertaining to this report should be directed to:

GEORGIA TECH'S FISCAL YEAR ENDS JUNE 30.

Ms. Geraldine Reese (404) 894-2629

Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

Signature of Authorized Certifying Official  David V. Welch, Director, Grants and Contracts Accounting	Telephone (Area code, number and extension)  (404) 894-2629
Signature of Authorized Certifying Official	Date Report Submitted  July 18, 1990

Attachment  
 07/18/90  
 Financial Status Report  
 Grant #DE-FG2205-88PC88918  
 Period Covered: 04/01/90 - 06/30/90

	<u>Direct Costs</u>	<u>Indirect Costs</u>
FY'89 @ 60.0%	\$33,363.21	\$20,017.94
FY'90 @ 62.5%	47,927.10	29,957.68

REPORT PERIOD

	<u>Direct Costs</u>	<u>Indirect Costs</u>
04/01/90 - 06/30/89 @62.5%	\$15,595.12	\$ 9,746.95

NON-FEDERAL

FY'89 @ 60.0%	\$ 2,085.00	\$ 1,251.00
FY'90 @ 62.5%		
10/01/89 - 12/31/89	647.84	404.90
01/01/90 - 03/31/90	685.64	428.52
04/01/90 - 06/30/90	704.70	440.45

# Georgia Tech

Office of Grants and Contracts Accounting

Georgia Institute of Technology

Hinman Building

Atlanta, Georgia 30332-0259

404-894-4624; 2629

Fax: 404-894-5519

October 31, 1990

Mr. John W. Meeker  
AD-22, MS 921-165  
U. S. Department of Energy  
Pittsburgh Energy Technology Center  
P. O. Box 10940  
Pittsburgh, PA 15236

SUBJECT: Grant No. DE-FG22-88PC88918

Dear Mr. Meeker,

Enclosed is the original Financial Status Report (SF-269) for Grant No. DE-FG22-88PC88918 covering the period July 01, 1990 through August 31, 1990 with copies being distributed in accordance with the report checklist.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch  
Director

DVW/GMR/djt

Enclosures

cc: U. S. Department of Energy  
Mr. Perry D. Bergman w/copy (1)  
Mr. Paul D. Gribble w/copy (3)  
Ms. Marilyn Keane w/copy (1)  
Mr. William J. Maro w/copy (1)  
Ms. Mary Wolfe, OCA/CSD 0420 ✓  
File E-16-A09/R6575-0A0

# FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted  U. S. DEPARTMENT OF ENERGY		2. Federal Grant or Other Identifying Number Assigned By Federal Agency  DE-FG22-88PC88918		OMB Approval No.  0348-0039	Page  1	of  pages			
3. Recipient Organization (Name and complete address, including ZIP code) GEORGIA TECH RESEARCH CORPORATION P. O. BOX 100117 ATLANTA, GA 30384									
4. Employer Identification Number  58-0603146		5. Recipient Account Number or Identifying Number  E-16-A09/R6575-0A0		6. Final Report <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		7. Basis <input checked="" type="checkbox"/> Cash <input type="checkbox"/> Accrual			
6. Funding/Grant Period (See Instructions) From: (Month, Day, Year) September 01, 1988		To: (Month, Day, Year) August 31, 1990		9. Period Covered by this Report From: (Month, Day, Year) July 01, 1990		To: (Month, Day, Year) August 31, 1990			
10. Transactions:				I Previously Reported		II This Period		III Cumulative	
a. Total outlays				\$137,913.98		\$8,727.07		\$146,641.05	
b. Recipient share of outlays				6,648.05		-0-		6,648.05	
c. Federal share of outlays				131,265.93		8,727.07		139,993.00	
d. Total unliquidated obligations								-0-	
e. Recipient share of unliquidated obligations								-0-	
f. Federal share of unliquidated obligations								-0-	
g. Total Federal share (Sum of lines c and f)								139,993.00	
h. Total Federal funds authorized for this funding period								139,993.00	
i. Unobligated balance of Federal funds (Line h minus line g)								\$ -0-	
Indirect Expense		a. Type of Rate (Place "X" in appropriate box) <input type="checkbox"/> Provisional <input type="checkbox"/> Predetermined <input type="checkbox"/> Final <input checked="" type="checkbox"/> Fixed							
		b. Rate See Attached		c. Base MTDC		d. Total Amount \$3,356.56		e. Federal Share \$3,356.56	
11. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.  Questions pertaining to this report should be directed to: Ms. Geraldine Reese (404) 894-2629									
12. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.									
Signature of Printed Name and Title  David V. Welch, Director, Grants & Contracts Accounting						Telephone (Area code, number and extension)  (404) 894-2629			
Signature of Authorized Certifying Official  <i>[Signature]</i>						Date Report Submitted  October 31, 1990			

Attachment  
10/31/90  
Financial Status Report  
Grant #DE-FG22-88PC88918  
Period Covered: 07/01/90 - 08/31/90

	<u>Direct Costs</u>	<u>Indirect Costs</u>
FY'89 @ 60.0%	\$33,363.21	\$20,017.94
FY'90 @ 62.5%	47,927.10	29,957.68
FY'91 @ 62.5%	5,370.51	3,356.56

REPORT PERIOD

	<u>Direct Costs</u>	<u>Indirect Costs</u>
07/01/90 - 08/31/90 @62.5%	\$5,370.51	\$ 3,356.56

GIT CONTRIBUTIONS

FY'89 @ 60.0%	\$ 2,085.00	\$ 1,251.00
FY'90 @ 62.5%	2,038.18	1,273.87

REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
FROM COAL BURNING PULSE COMBUSTORS

Quarterly Technical Progress Report  
for the Period September 1, 1988 - December 31, 1988

By

E. A. Powell and B. T. Zinn

January 1989

Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy  
Office of Fossil Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania 15236

By

School of Aerospace Engineering  
Georgia Tech Research Corporation  
Georgia Institute of Technology  
Atlanta, GA 30332

TECHNICAL INFORMATION CENTER  
OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION  
UNITED STATES DEPARTMENT OF ENERGY

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## TECHNICAL STATUS

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COAL PULSE COMBUSTION RESEARCH

Quarterly Technical Progress Report for the  
Period September 1, 1988 - December 31, 1988

Prepared by

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January 1989

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Prepared for

United States Department of Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

## ABSTRACT

Work accomplished during the first quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of the  $\text{NO}_x$  and  $\text{SO}_2$  emissions from Rijke type pulse coal combustors by using combustion staging and limestone addition. Most of the work accomplished during this period was concerned with the design and fabrication of the Rijke tube combustor, the coal feed system and the limestone feed system. The combustor was designed to be operated in either a 3 m or 6 m long configuration with a fixed coal bed location. The limestone and coal feed systems utilize motor driven augers to deliver the materials at controlled rates. The pulverized limestone feed system was designed to introduce 50 micron limestone particles into an air stream and to inject them just above the coal bed. The design of the major components was completed during the report period, and fabrication of some of these components was begun during the last month of this period.

## INTRODUCTION

The following report summarizes the work done under DOE Grant No. DE-FG22-88PC88918 during the period September 1, 1988 through December 31, 1988. This project is a continuation of earlier work done at Georgia Tech which demonstrated that unpulverized coals, both bituminous and subbituminous, can be burned with efficiencies greater than 97% in Rijke type pulse combustors with only 10% excess air. In Rijke combustors the coal is burned in a bed where the presence of acoustic velocity oscillations results in bed fluidization and the intensification in the rates of mass, momentum, and heat transfer processes; phenomena which are apparently responsible for the superior performance of the pulse combustor. The objective of this project is to determine if the nitrogen oxides and sulfur dioxide emissions can be reduced by staging the combustion process and by adding limestone or dolomite to the acoustically fluidized bed or to the flow of combustion gases above the bed.

Most of the work accomplished during this reporting period was concerned with the design of the Rijke type pulse combustor, the coal feed system, and the limestone feed system. The design of the major components was completed during the report period, and fabrication of some of these components was begun during the last month of this period.

### RIJKE TUBE COAL COMBUSTOR

The Rijke tube pulse coal combustor basically consists of a vertical tube which is open at both ends with a combustion zone (coal bed) located one quarter of the distance from the lower end of the tube to the upper end. The combustion process interacting with the mean flow through the tube excites the fundamental axial acoustic mode for an open-ended tube. For this mode the pressure oscillations are a maximum at the middle of the tube, while the acoustic velocity oscillations are a maximum at the ends of the tube. The open-ended boundary condition requires the pressure perturbations to be zero at the ends of the tube. The lower end of the tube is connected to an acoustic decoupler, which is a section of pipe with a much greater cross-sectional area than the Rijke tube itself. This preserves the open-ended boundary condition, while allowing control of the air flow through the combustor. The basic Rijke tube geometry along with the fundamental mode pressure and velocity profiles are shown in Figure 1.

The Rijke tube coal combustor to be used in this investigation has been designed to allow operation at two different pulsation frequencies by changing the length of the tube, while maintaining the combustion at the quarter-length point. This was accomplished by means of a vertical insulated pipe section 183 cm long (72 in), which contains the coal bed, to which various horizontal pipe sections can be added. The two configurations are shown in Figure 2.

In the short configuration, which has a total length of 3.05 m (10 ft), a vertical section of uninsulated pipe is connected to the top of the insulated section. The bottom of the insulated section is connected to the decoupler by means of an elbow and a short horizontal pipe section.

In the long configuration, which has a total length of 6.10 m (20 ft), two additional lengths of horizontal pipe are added. At the bottom (decoupler) end of the system, a 76 cm (30 in) pipe section is inserted between the

elbow and the short pipe section connected to the decoupler. At the top (exhaust) end, the vertical pipe is replaced by an elbow and a 1.93 m (76 in) horizontal section of pipe which is connected to a second elbow and a short section of pipe leading to the exhaust. In both configurations the coal bed is located 12.7 cm (5 in) above the lower end of the vertical insulated pipe section.

The vertical insulated section is shown in more detail in Figure 3 along with the coal feed system and the limestone feed system. The Rijke tube is made from 25.4 cm I.D. (10 in) steel pipe lined with 5 cm (2 in) of castable ceramic insulation leaving a central bore diameter of 15 cm (6 in). The coal bed will be provided with water cooling tubes for control of the combustion zone temperature which is necessary for NO<sub>x</sub> control and efficient SO<sub>2</sub> removal by the limestone sorbent. A natural gas line will be provided for preheating the combustor and ignition of the coal. The water and natural gas lines are contained in a central bundle extending upwards from the bottom of the Rijke tube.

All of the steel pipe and other materials needed for construction of the Rijke combustor have been obtained, and fabrication of the components in the Aerospace Engineering machine shop facilities has begun. The decoupler section has been completed, and the other components are expected to be finished by the middle of February. The components will then be assembled in the Aerospace Engineering Combustion Laboratory facilities by the end of February.

#### COAL FEED SYSTEM

The coal is fed into the combustion tube by means of a motor driven auger which is supplied by a hopper as shown in Figure 3. A self-feeding auger is used which has a diameter of 3.8 cm (1.5 in) and a pitch of 2.5 cm (1.0 in) at the feed end and a diameter and pitch of 1.9 cm (0.75 in) at the delivery end. The total length of the auger is 64 cm (25 in). The crushed coal particles, which range in size from 3 mm to 6 mm, travel up the auger tube and enter a downward sloping feed tube which leads into the Rijke tube a distance  $h$  above the coal bed. The inclination angles of the auger and feed tubes and the distance  $h$  will be determined experimentally before assembly to obtain uniform distribution of the coal particles on the bed. The speed of the auger can be varied to deliver coal at rates ranging from about 2 kg/hr to about 8 kg/hr.

The auger has been obtained from the manufacturer, and the fabrication of the hopper and auger tube has been completed. The drive motor, gear train, and motor speed controller have also been obtained. Assembly of the feed system is expected to be finished by the end of February.

#### LIMESTONE FEED SYSTEM

Limestone and dolomite sorbents will be utilized for SO<sub>2</sub> removal. Two methods of limestone delivery will be investigated in this project.

In the first method, crushed limestone or dolomite will be mixed with the coal in the proper proportion to give the desired Ca/S ratio. The limestone-coal mixture will be fed to the combustor through the coal feed system

described above. This method of delivery will be used for crushed limestone or dolomite with a mean particle diameter of about 0.5 mm.

In the second method, pulverized limestone or dolomite with a mean particle diameter of about 0.05 mm (50 microns) will be entrained into an air stream and injected into the combustor just above the coal bed. The pulverized limestone injection system is also shown in Figure 3. Here limestone in a hopper is delivered by a vertical auger into a venturi where it is entrained into the air flow. The suspended limestone particles travel through a 0.95 cm diameter (0.375 in) stainless steel tube down the axis of the Rijke tube to the injector head. As they move down the central tube, they are expected to be heated sufficiently so that significant calcination of the limestone occurs before injection into the Rijke tube. The partially calcined sorbent particles are injected radially into the combustion gases just above the coal bed, and they are then carried up the Rijke tube by the mean flow. During their travel up the Rijke tube, sulfation reactions with  $\text{SO}_2$  are expected to occur, thus removing  $\text{SO}_2$  from the exhaust gases.

The pulverized limestone feed system has been designed to deliver limestone at rates ranging from about 1 g/min to about 40 g/min into an air flow which amounts to only about one percent of the combustion air flow through the Rijke tube. A detail of the auger feed system is shown in Figure 4. The auger used has a diameter of 9.5 mm, a root diameter of 4.8 mm, a pitch of 6.4 mm, and a length of 16.2 cm. The auger can be driven at speeds ranging from 1 to 100 rpm to obtain the desired feed rates. The venturi provides increased air velocity at the point where the auger delivers the pulverized limestone to the air stream in order to get good entrainment of the particles.

A detail of the injector head is given in Figure 5. The injector head consists of a conical nozzle section with a conical centerbody. This directs the axial flow in the delivery tube radially outwards into the combustion gases. The exit gap can be adjusted in order to obtain the optimum injection velocity for dispersing the sorbent particles over the cross-section of the Rijke tube.

#### FUTURE WORK

Fabrication of the Rijke tube pulse coal combustor and all of its auxiliary systems is expected to be completed by the end of February. The components will then be assembled in the Aerospace Engineering combustion laboratory. A series of preliminary tests will then be conducted to check out the various systems and to determine the proper operating parameters. This will include calibration of the coal and limestone feed system. During the latter part of the next quarter, a series of baseline tests will be conducted to determine the  $\text{NO}_x$  and  $\text{SO}_2$  emissions in the absence of the proposed control measures such as combustion staging or limestone injection.

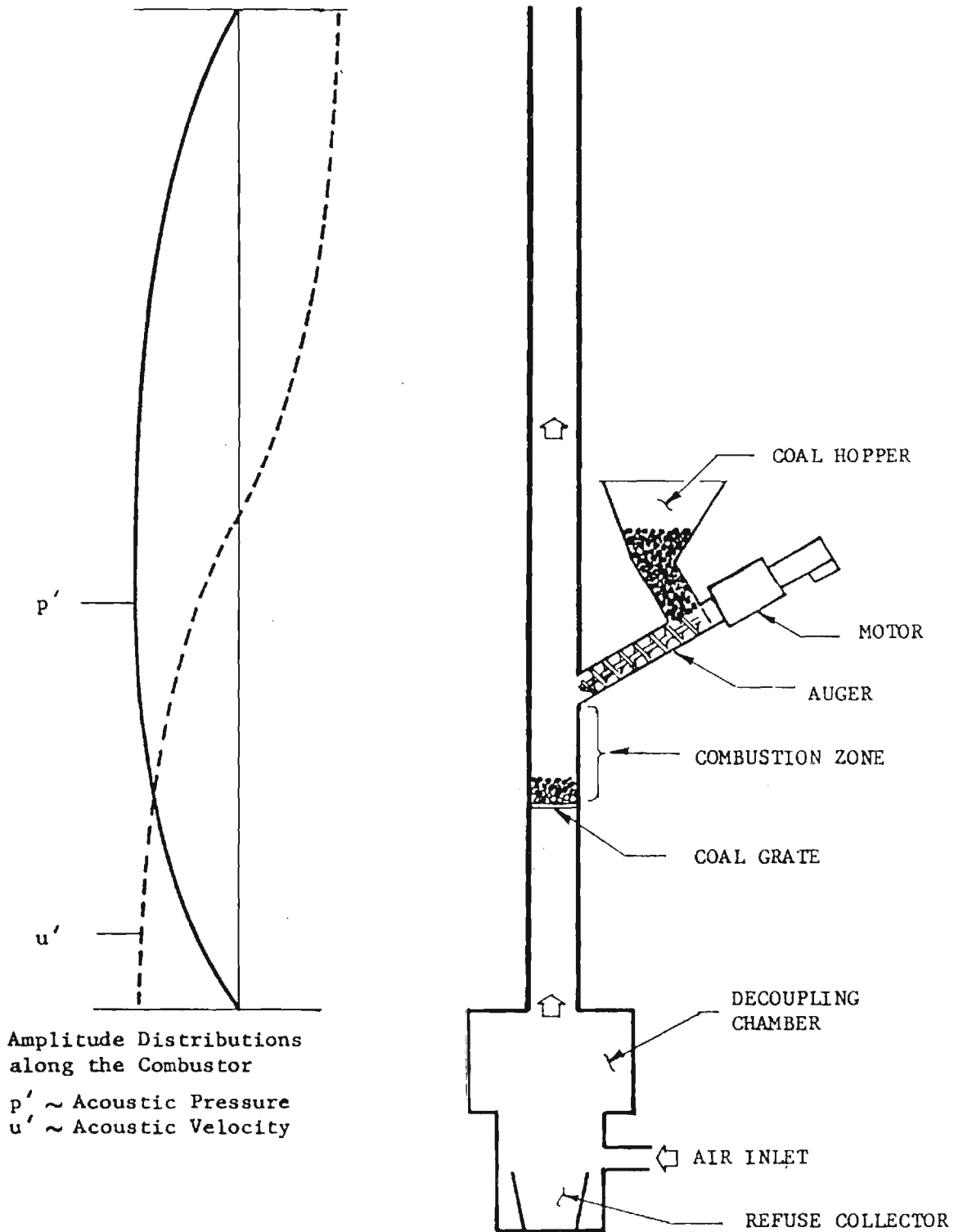


Figure 1. A Schematic of the Coal Burning Rijke Tube Pulsating Combustor Developed at Georgia Tech and Its Acoustic Wave Structure.

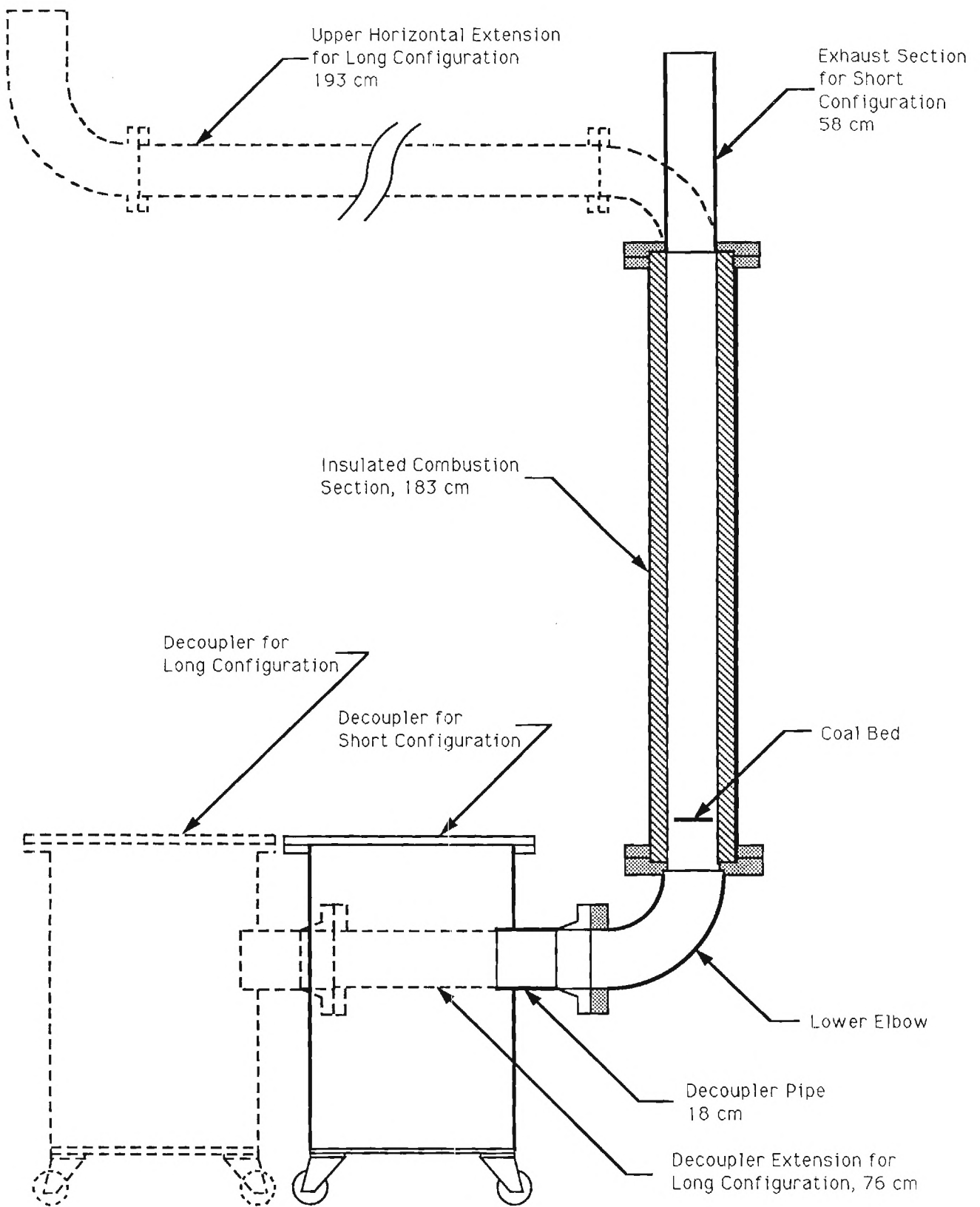


Figure 2. Rijke Pulse Combustor Configurations

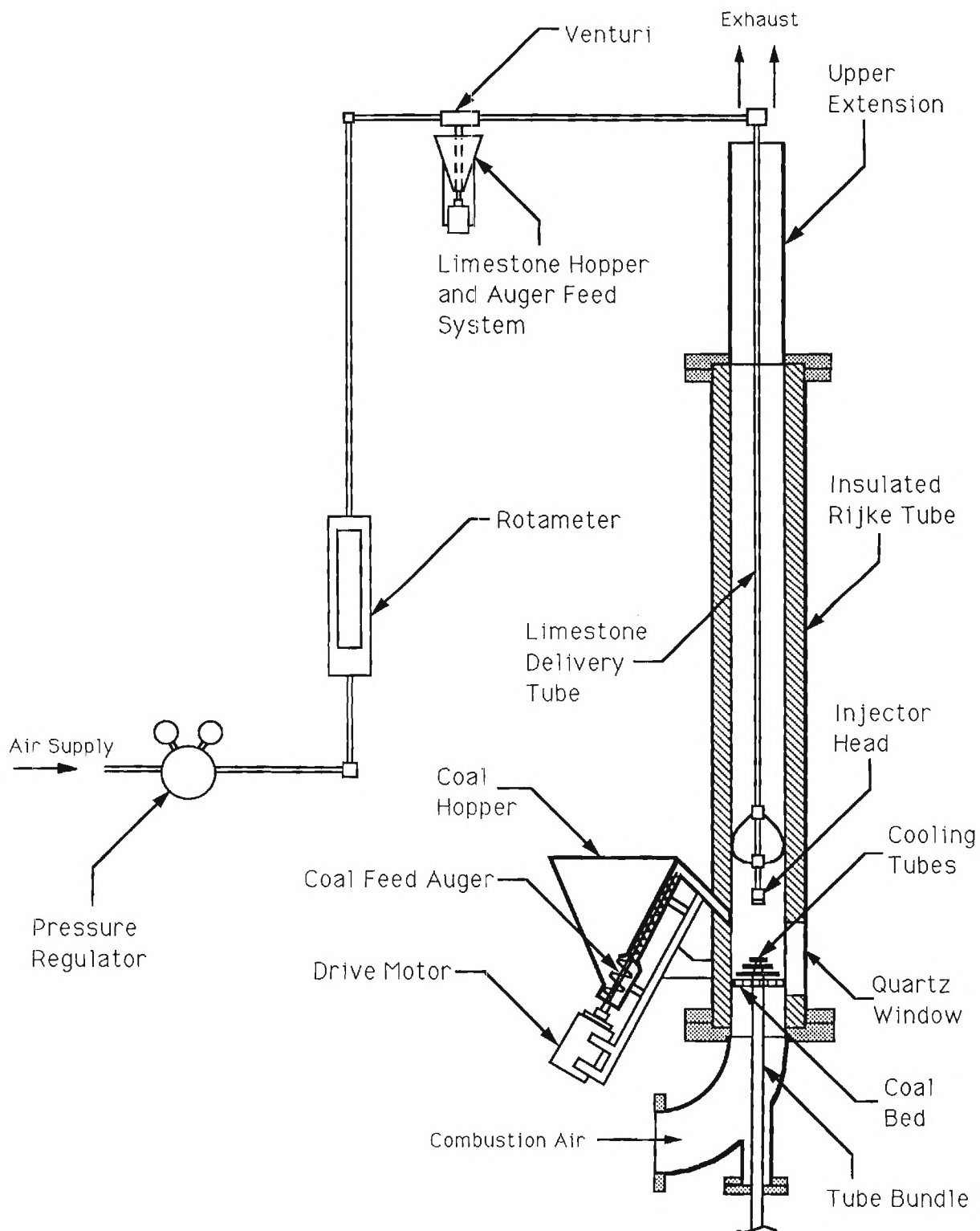


Figure 3. Rijke Combustor with Coal and Limestone Feed Systems

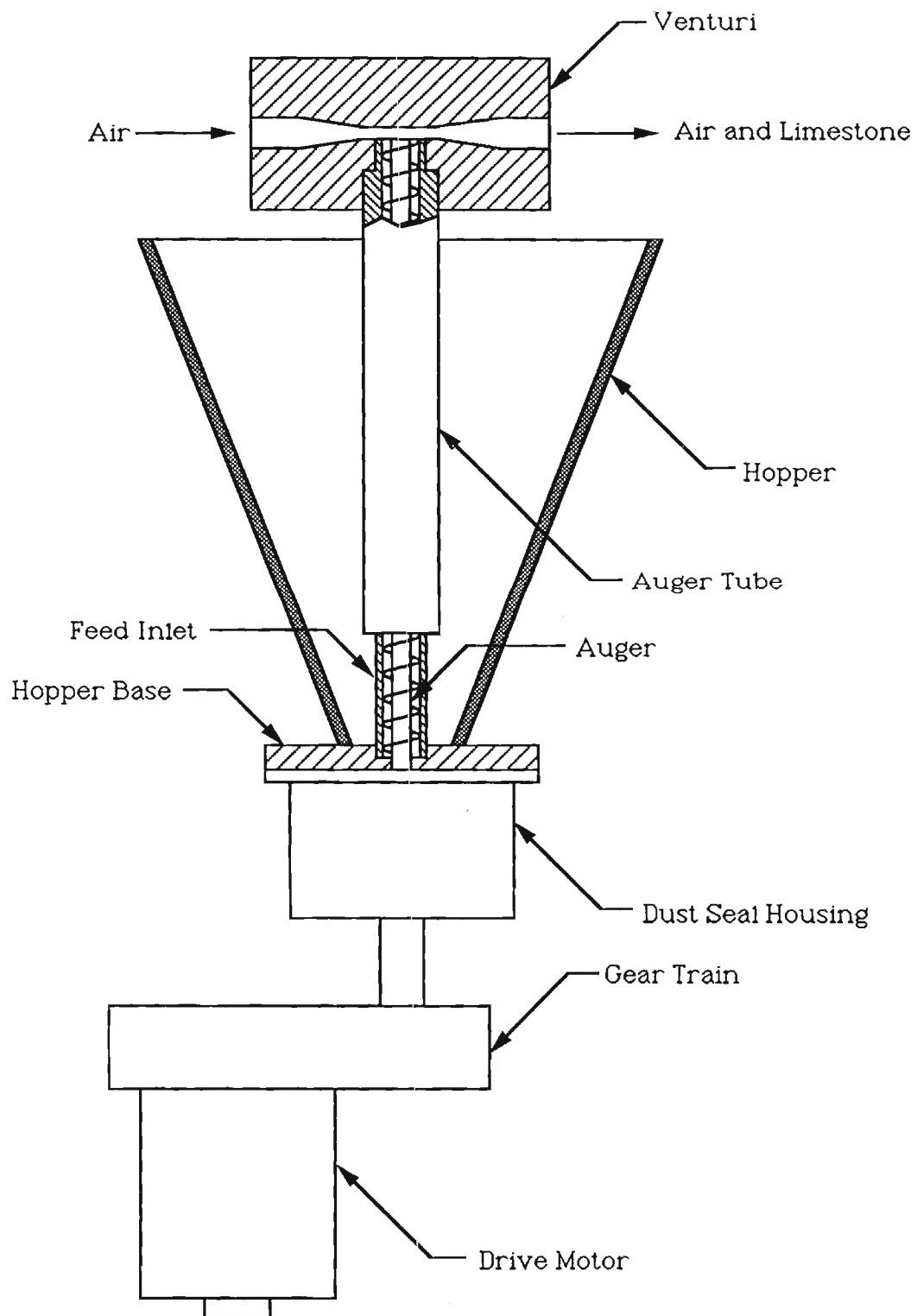


Figure 4. Limestone Auger Feed System

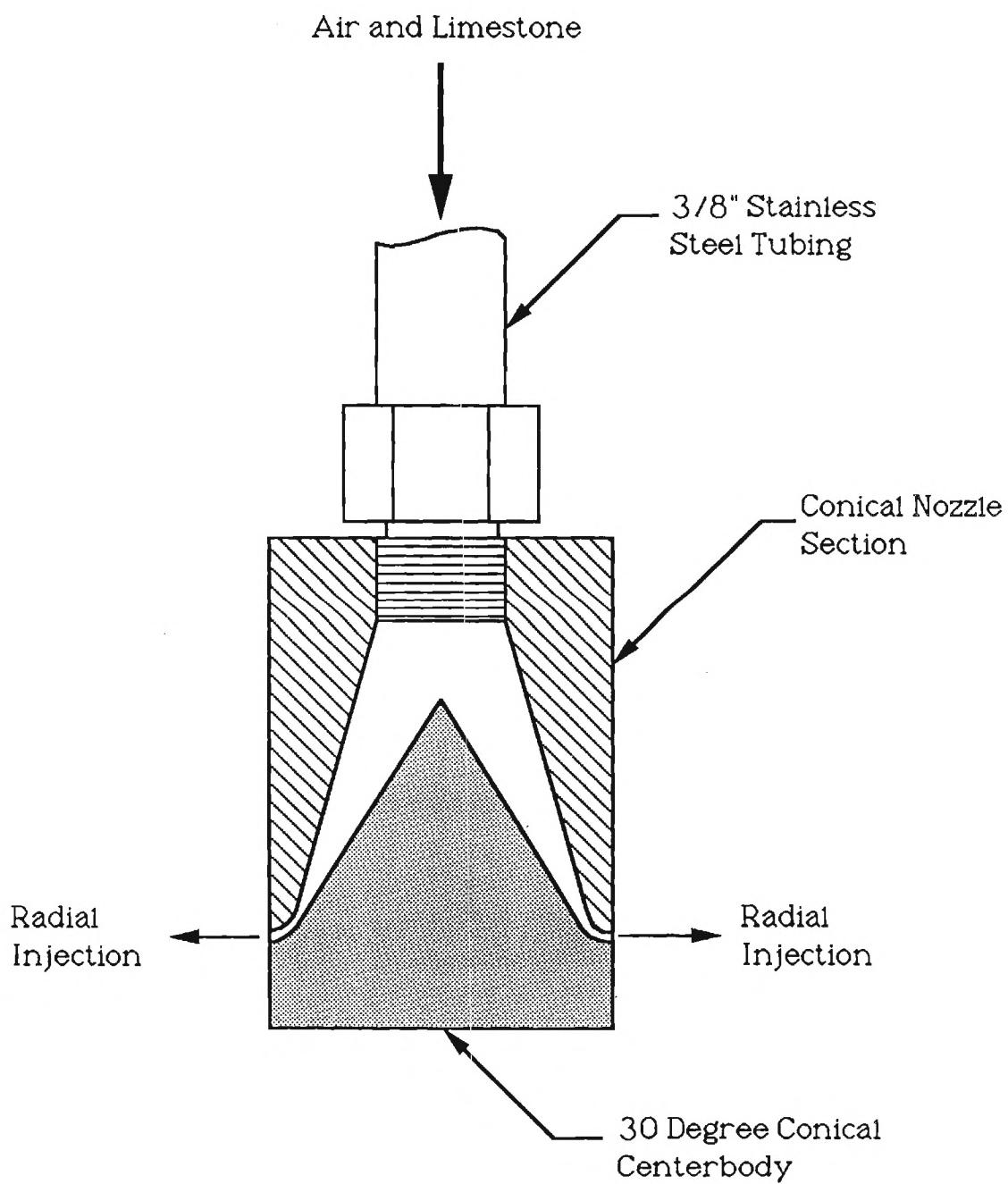


Figure 5. Limestone Injector Head

REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
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E. A. Powell and B. T. Zinn

April 1989

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For

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Office of Fossil Energy  
Pittsburgh Energy Technology Center  
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April 1989

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Prepared for

United States Department of Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

## ABSTRACT

Work accomplished during the second quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of the nitrogen oxides and sulfur dioxide emissions from Rijke type pulse combustors by using combustion staging and limestone addition. Most of the work accomplished during this period was concerned with the design and fabrication of several auxiliary systems needed for operation of the Rijke combustor. These include the coal feed system, the limestone feed system, the coal bed, the bed temperature control system, and the ignition and preheating system. Each of these systems is described in the report. Finally, plans for the third quarter of the project are outlined.

## INTRODUCTION

The following report summarizes the work done under DOE Grant No. DE-FG22-88PC88918 during the period January 1, 1989 through March 31, 1989. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

Most of the work accomplished during this reporting period was concerned with the design and fabrication of auxiliary systems needed for operation of the experimental pulse combustor. These included the coal and limestone feed systems, the coal bed, the bed temperature control system, and the ignition and preheating system. The design and fabrication of these systems was completed during the reporting period. In addition the fabrication of the combustion section shell and the extension pipe sections and elbow adapters was completed during this period.

## COAL FEED SYSTEM

The motor driven auger coal feed system was assembled and tested using crushed bituminous coal with particle sizes ranging from approximately 1 mm to 1 cm in diameter. In these tests the auger delivered the coal upward from a hopper into a downward sloping tube leading into a vertical plastic pipe with the same diameter as the combustion section. The angle of the auger tube and the delivery tube could be varied, as well as the height of the delivery tube exit above the coal bed. A mock-up of the coal bed and water cooling tubes above the bed was inserted into the plastic pipe at the desired height, and the distribution of the coal falling on the bed was observed.

During the initial tests it was soon discovered that the 1.9 cm diameter auger could deliver only about 30% to 50% of the required coal feed rates even at maximum auger speed (about 20 RPM). Therefore a larger auger (3.8 cm diameter) was obtained and the auger tube and delivery tube were redesigned.

After fabrication of the modified auger feed system was completed, the tests of the coal feed system were resumed. It was determined from these tests that the most uniform distribution of coal on the bed was obtained with the bottom of the delivery tube about 15 cm above the coal bed. Also the optimum delivery tube slope was found to be 35 degrees from the vertical, and the auger functioned best at about 8 degrees from the vertical.

The above parameters were incorporated into the final design of the coal feed system which is shown in Figure 1. The variable speed motor is coupled to the auger shaft by a universal joint in order to prevent problems due to any slight misalignment of the motor shaft with the auger shaft.

Fabrication of the modified water-cooled delivery tube, which is shown in Figure 2, has been completed. The inner pipe of the delivery tube is the same diameter as the auger tube (4.25 cm I.D.), and the outer pipe forming the water jacket has an inside diameter of 6.32 cm. Water enters the cooling jacket through a 6.4 mm O.D. stainless steel tube extending nearly to the lowest (and hottest) end of the annular water cavity and exits through another stainless steel tube near the top on the opposite side. The water cooling is needed primarily to prevent the coal from sticking to the inside of the

delivery tube and eventually blocking the tube. The coal feed tube was also provided with a viewing window at its upper end to facilitate the determination of the cause of any failure of the auger to feed properly.

With the coal feed system parameters determined, the fabrication of the Rijke tube combustion section shell was completed with the drilling of the slanted hole for the coal delivery tube.

#### LIMESTONE FEED SYSTEM

Fabrication of the auger feed system, limestone hopper, venturi, and injector head have been completed. These components were described in the previous Technical Progress Report. Assembly of these components will be done when the Rijke tube combustor is assembled in the laboratory building.

#### COAL BED

The design and fabrication of the coal bed was completed during the report period. The general location and side view of the coal bed is shown in Figure 3, which also shows several other combustor systems. A top view of the coal bed is shown in Figure 4. The bed consists of two semi-circular sections which are pivoted to allow accumulated ash to be dumped periodically. The top of the bed was cut from a #6 mesh stainless steel grid which will retain coal particles larger than about 3 mm in diameter. The mesh is welded to a stainless steel frame which is also shown in Figure 4. The frame is removable for ease in cleaning, being attached to the pivot rods by means of stainless steel clips. A central hole is provided in the bed for the water lines and supports for the bed temperature control system.

A cross-section of the bed-section of the combustor with the bed removed is shown in Figure 5. The bed pivot rods are supported by 3.2 mm diameter stainless steel rods extending to the outside through pivot bearing tubes which penetrate the combustion shell and insulation. The pivot bearing tubes are made from short sections of 6.4 mm O.D. stainless steel tubing which will be welded to the inside of the combustion section shell prior to casting of the insulation. For each half of the bed one of the 3.2 mm rods is bent to form a lever which is provided with a counterweight. The counterweight prevents the coal from being dumped under its own weight during operation of the combustor. When necessary, the ash is dumped by lifting the counter-weighted lever off its stop.

#### BED TEMPERATURE CONTROL SYSTEM

The bed temperature control system was designed and fabricated during the report period. This system consists of water cooling tubes inserted into the coal bed and extending a few centimeters above the coal bed. This system is needed in order to maintain the temperature in the combustion region between 850 C and 980 C to promote optimal sulfur retention by the limestone and dolomite sorbents. In addition, control of the temperature in the primary combustion zone is needed in the reduction of nitrogen oxides production by combustion staging.

The water cooling tubes are shown in Figure 3. There are two separate cooling stages which supply cooling water at three levels above the coal bed.

In each stage the water supply and return lines are attached to central stainless steel columns which lie along the vertical axis of the combustion tube and pass through the central hole in the coal bed. Both stages are constructed of 6.4 mm O.D. stainless steel tubing.

The first stage cooling loop, which is shown in Figure 6, consists of an inner and an outer loop formed from a continuous section of stainless steel tubing. The water flows through the outer loop first and then through the inner loop. The height of this stage above the coal bed grid is adjustable, allowing the cooling tubes to be located within or just above the coal bed.

The second stage cooling loops, which are shown in Figure 7, provide cooling water at the second and third level above the coal bed. The water first flows through the lower loop, which is fixed at 2.5 cm above the first stage cooling loops, and then through the upper loop, which is 2.5 cm above the lower loop.

The water flow rates in the first and second stages can be varied independently in order to control the temperature in the coal bed and its variation with height above the coal bed. The entire cooling assembly can be moved vertically to provide additional temperature control and to facilitate installation of the coal bed assembly.

#### IGNITION AND PREHEATING SYSTEM

The ignition and preheating system was designed and fabricated during the second quarter of this project. The igniter and preheater ring is shown in Figure 3 where it is located below the coal bed. A detail of the igniter and preheater ring is shown in Figure 8. This consists of a 10 cm diameter loop of 6.4 mm O.D. stainless steel tubing which is closed at the end. Premixed natural gas and air enters the loop from the central supply line and exits through several 1.6 mm diameter holes drilled in the top of the ring. The gas/air mixture is ignited by an electric spark and burns in the region between the ring and the base of the bed. This system is used to preheat the Rijke tube combustor and ignite the coal during the start-up process. The igniter and preheater ring will also be used to heat the combustion section (with bed and cooling loops removed) during the curing of the castable ceramic insulation.

#### FUTURE WORK

During the third quarter of the project, it is expected that the fabrication of the remaining components will be completed. These include observation windows for the insulated combustor section and mounts for the limestone auger feed system. The components will then be assembled in the laboratory building and the ceramic insulation will be cast in the combustion section. Air lines, water lines, and gas lines will then be installed along with flow metering equipment. The natural gas igniter and preheating system will then be used for curing the ceramic insulation. Instrumentation for temperature and acoustic pressure measurements will be installed. The gas analysis system will be installed and calibrated, and a gas sampling probe will be obtained.

After all systems are assembled testing will begin. A series of preliminary tests will be conducted to check out the various systems and to obtain

the operating characteristics of the combustor. The baseline tests will then be begun in order to determine the sulfur dioxide and nitrogen oxides emissions of the combustor in the absence of limestone addition or combustion staging.

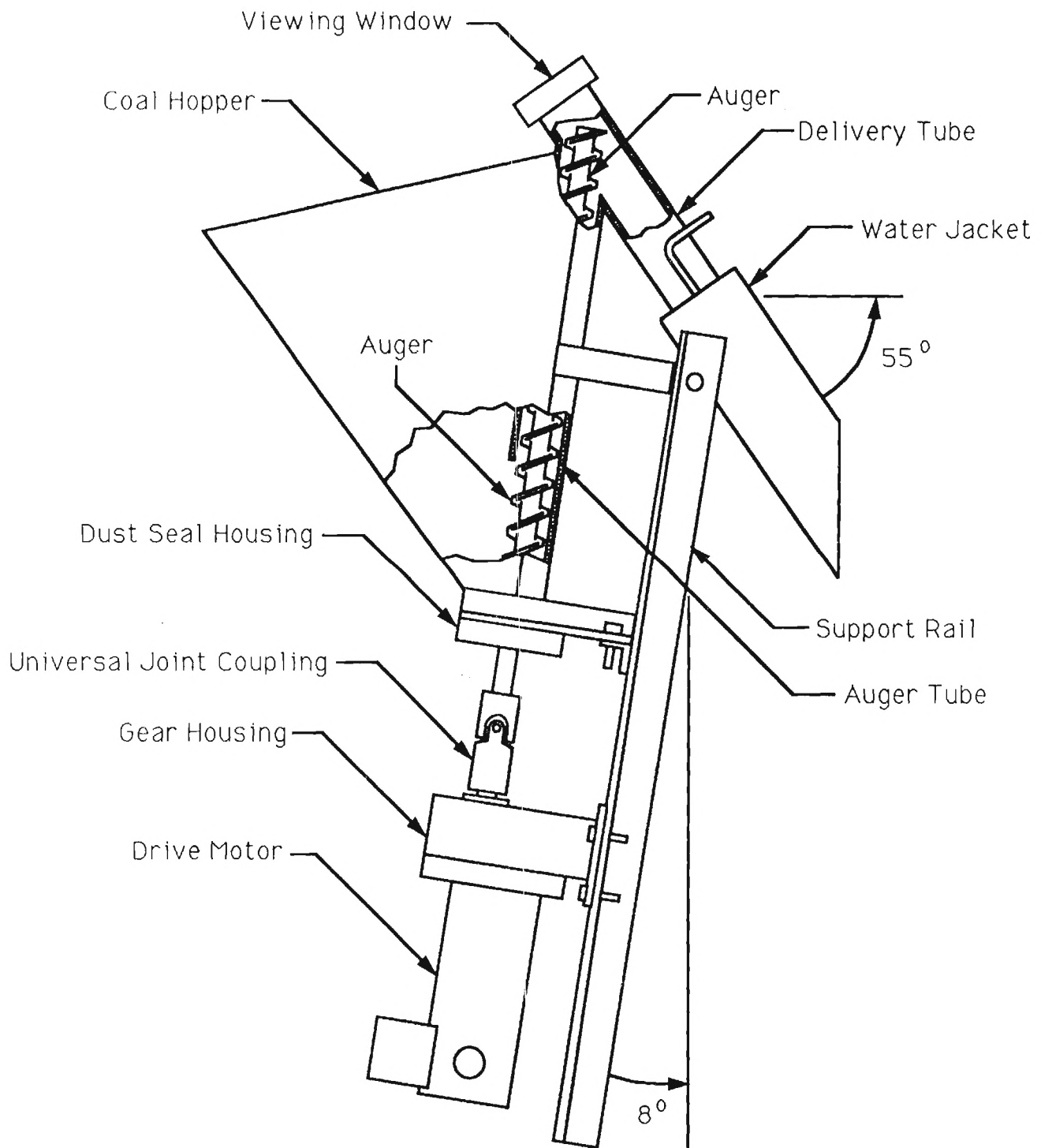


Figure 1. Coal Feed System

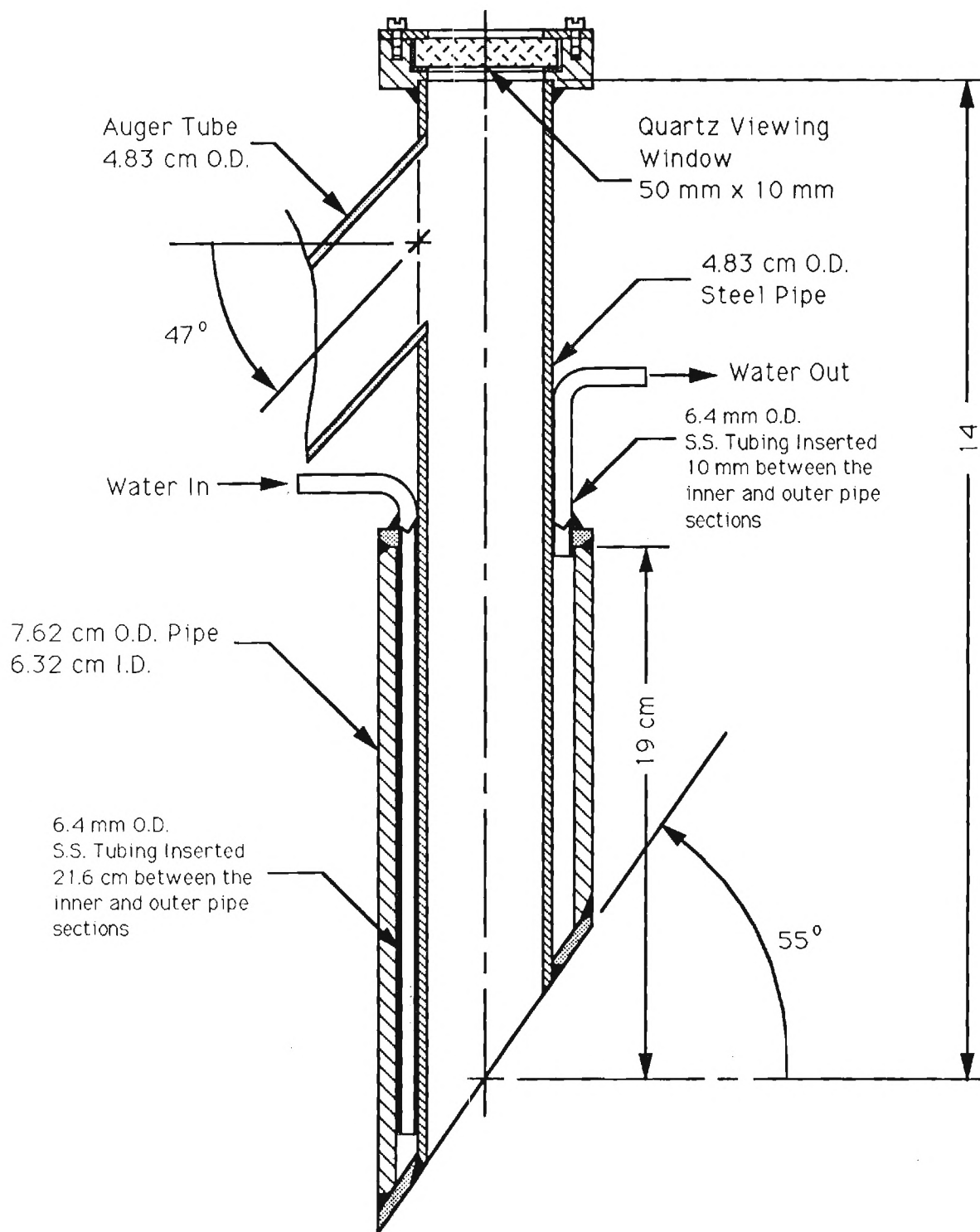


Figure 2. Water Cooled Coal Delivery Tube.

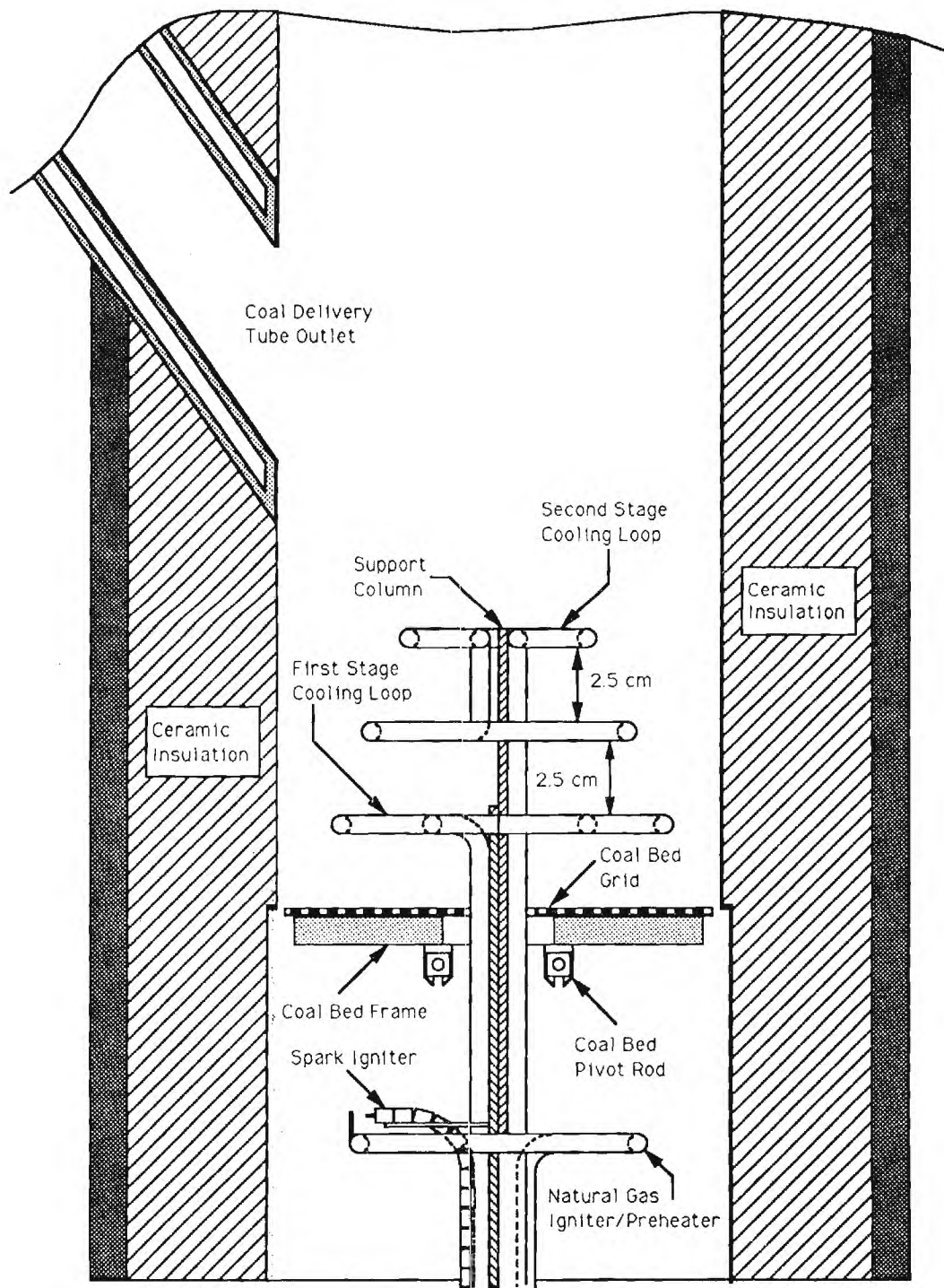


Figure 3. Longitudinal Section of Combustion Region

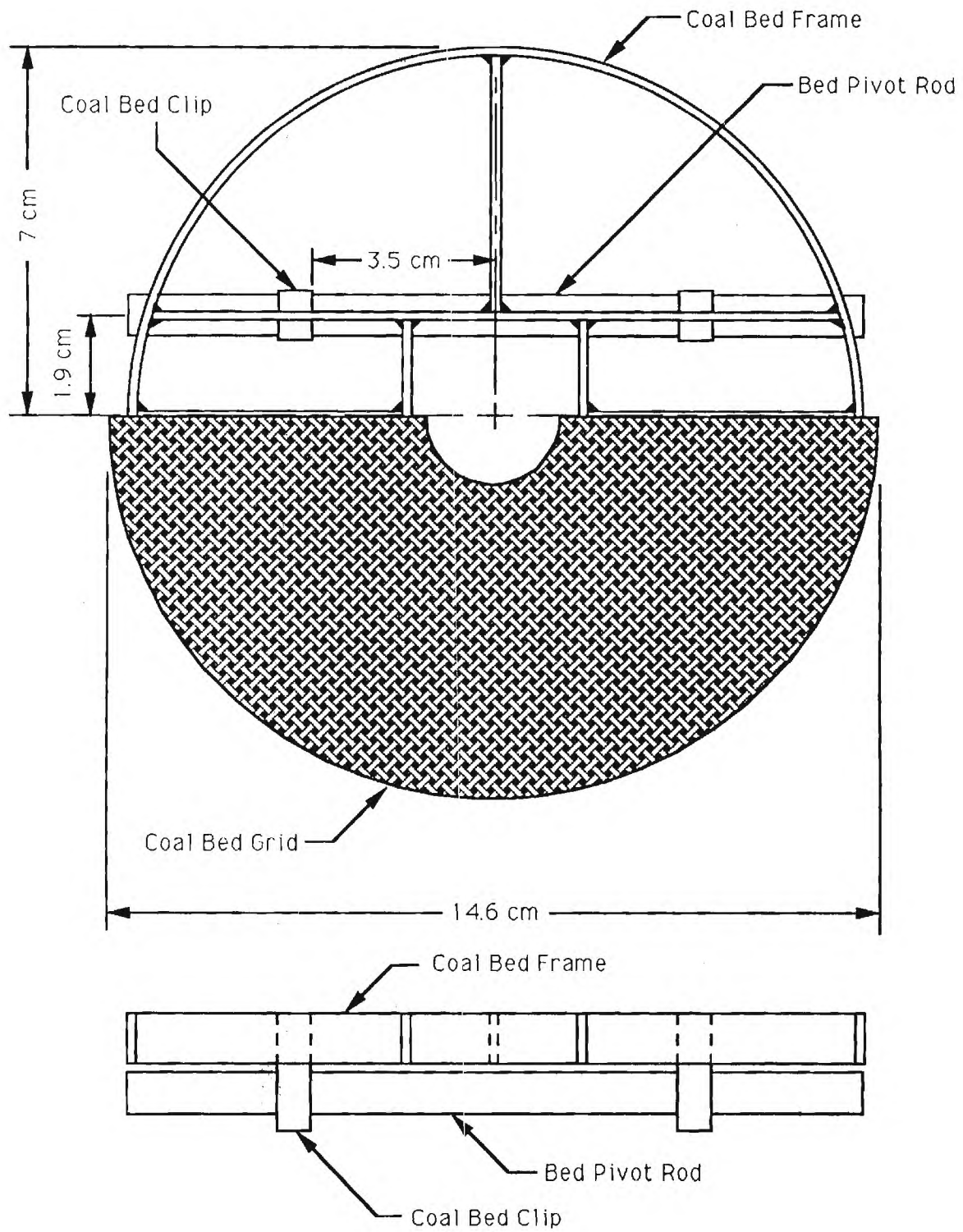


Figure 4. Detail of Coal Bed

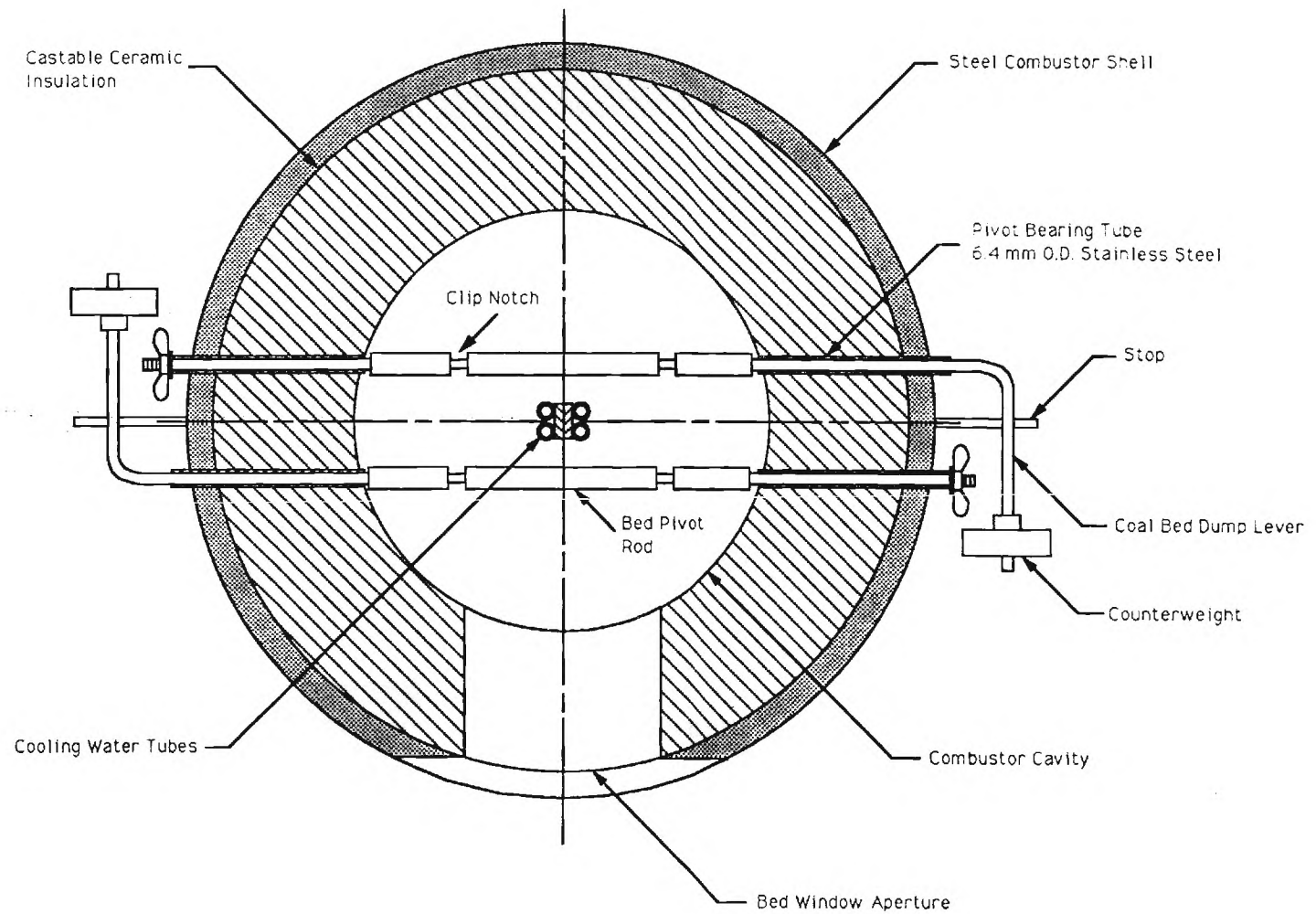


Figure 5. Cross-section of Combustor at Bed Level

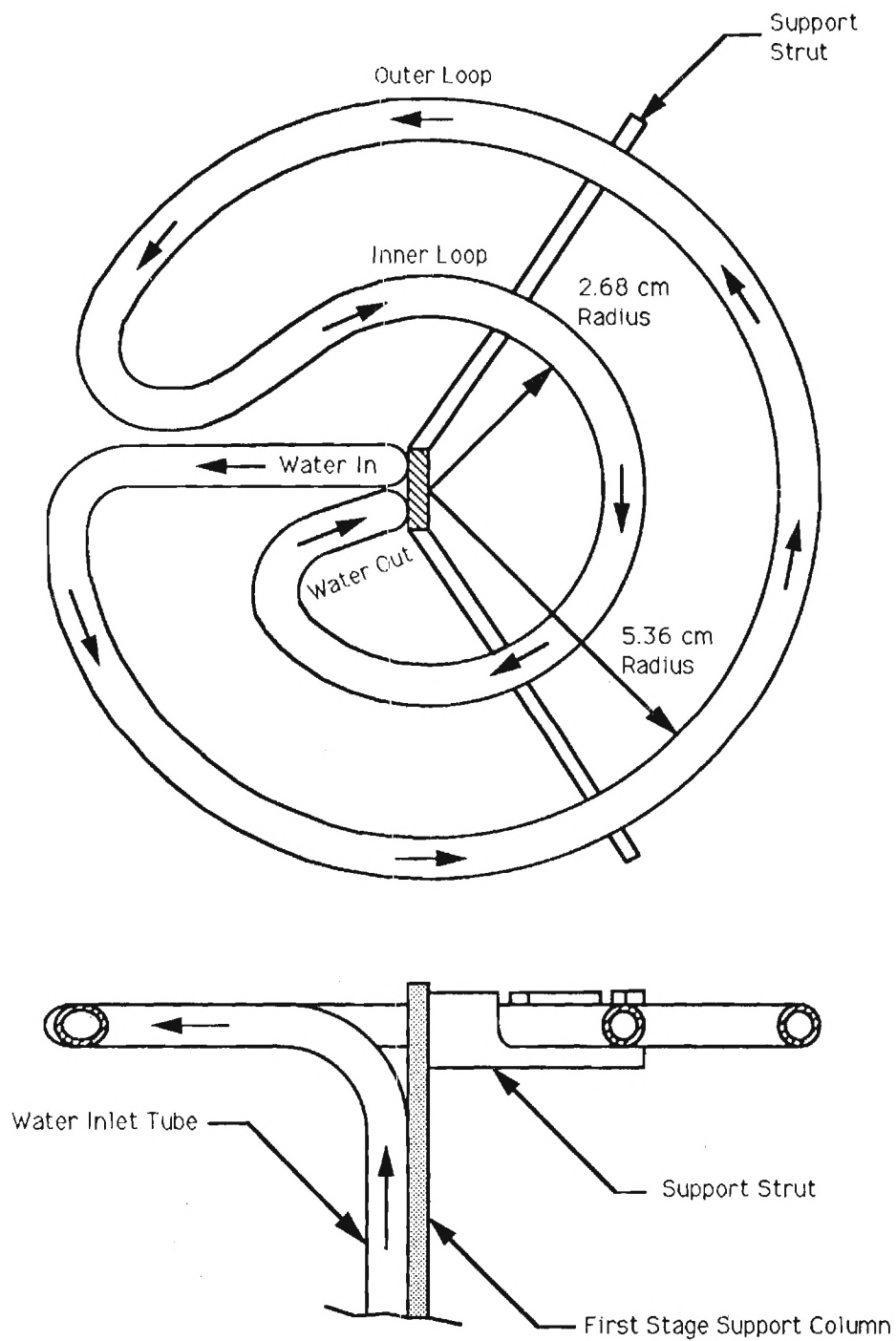


Figure 6. First Stage Cooling Loop

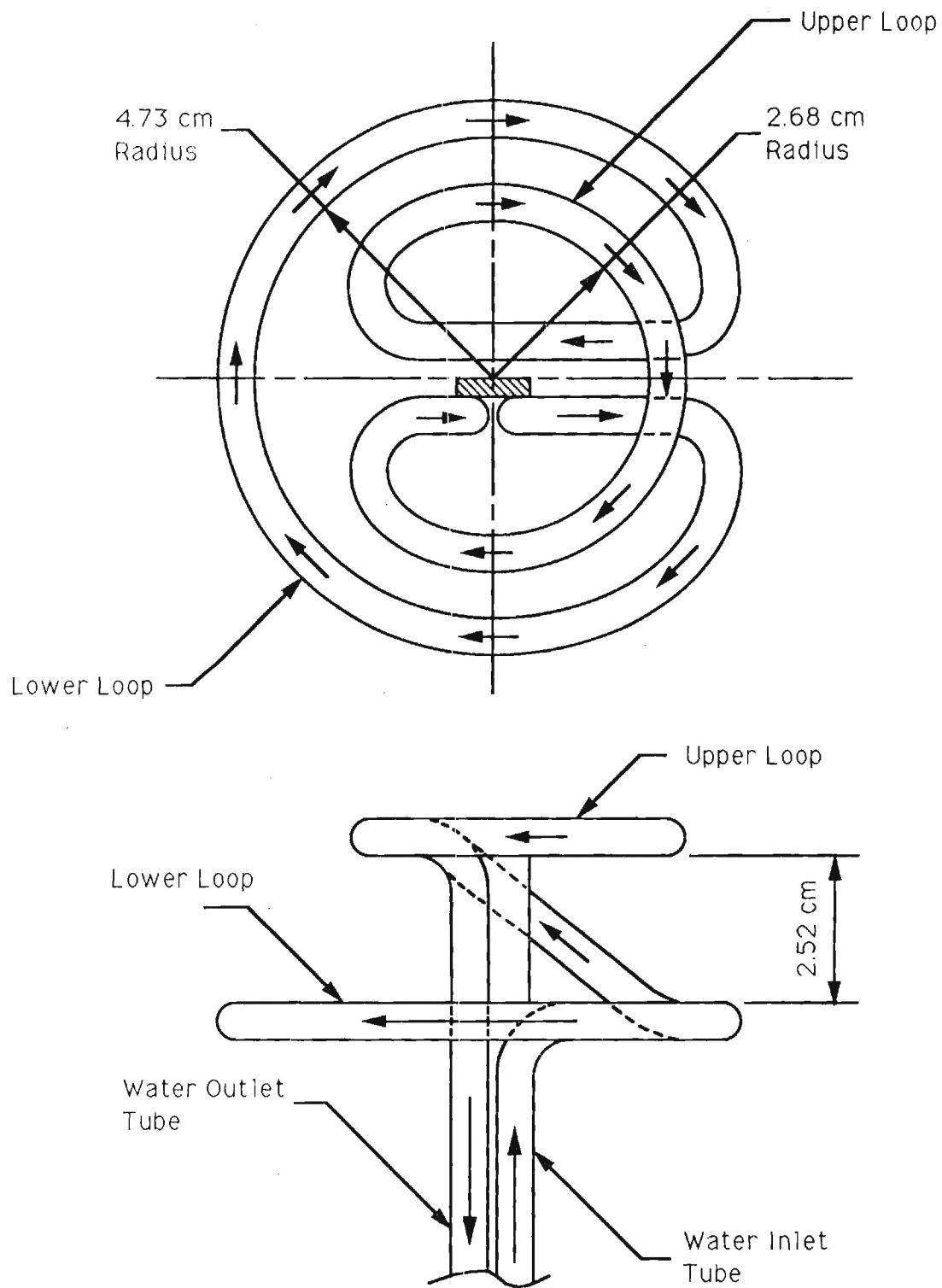


Figure 7. Second Stage Cooling Loop

1.6 mm Diameter  
Holes approximately  
12.5 mm apart

6.4 mm O.D.  
Stainless Steel  
Tubing

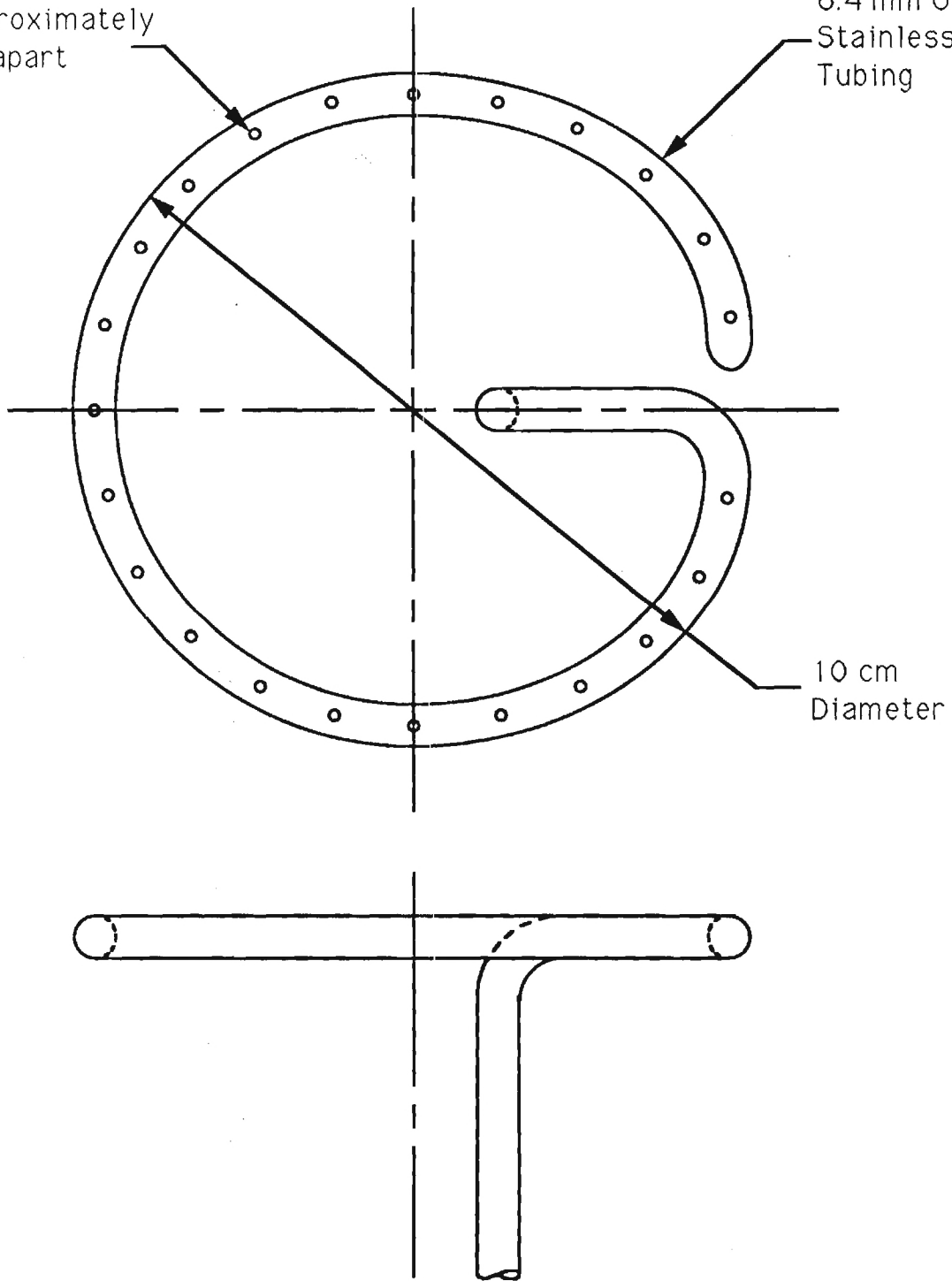


Figure 8. Igniter - Preheater Ring

REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
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## ABSTRACT

Work accomplished during the third quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of the nitrogen oxides and sulfur dioxide emissions from Rijke type pulse combustors by using combustion staging and limestone addition. During this quarter, the fabrication and assembly of the Rijke tube coal burning pulse combustor was completed. This included the casting of the ceramic insulation for the combustor section and installation of the observation windows, the coal bed and cooling system, the coal feed system, the air supply system, the gas igniter and preheater system, instrumentation for measurement of temperatures and acoustic pressures, and the exhaust gas sampling probe and analysis system. Each of these systems is described in this report. The results of preliminary tests using natural gas as fuel are also described. The effect of varying air flow rate and burner position on the pulsation amplitude was determined, as well as the minimum and maximum air flow rates for which pulsating operation occurred. The maximum amplitude was about 142 dB at a frequency of about 70 Hz. The occurrence of pulsations was sensitive to burner position. Finally, plans for the fourth quarter of the project are outlined.

## INTRODUCTION

The following report summarizes the work done under DOE Grant No. DE-FG22-88PC88918 during the period April 1, 1989 through June 30, 1989. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

### FABRICATION OF COMPONENTS AND ASSEMBLY OF SYSTEM

During the third quarter of the project the fabrication and assembly of the Rijke tube pulse combustor was completed. This included fabrication and installation of the observation windows for the insulated combustor section, casting of the ceramic insulation for the combustor section, installation of the coal bed and bed cooling system, modification and installation of the coal feed system, installation of air, water, and gas lines, installation of the natural gas igniter and preheater system, installation of instrumentation for measurement of temperature and acoustic pressure measurements, and installation of the exhaust gas sampling probe and analysis system. These items will be discussed in more detail in the remainder of this section.

#### Observation Windows

The insulated combustor section was provided with three quartz observation windows which are 30.5 cm long, 6.4 cm wide, and 1.9 cm thick. These are located at the bed level, the center, and the upper end of the combustion section. Each window is seated in a stainless steel frame which is welded into a hole cut in the steel combustor shell (Figure 1). Quartz felt strips were installed around the perimeter of each window and cemented in place using high temperature RTV compound. These provide a buffer between the quartz window and the steel window frame. Each window is held in place using ten bolt-mounted clips.

#### Ceramic Insulation

The ceramic insulation was cast and cured during this report period. This process required considerable preparation of the combustor shell. Small steel nuts were first welded to the inside of the steel shell about 30 cm apart to hold the ceramic insulation in place. Then a central core consisting of thin-walled acrylic plastic pipe (15.2 cm O.D.) was installed in the combustor shell. This pipe was coated with wax and scored with longitudinal grooves in order to facilitate removal after the ceramic had set. Similarly, cores were fabricated and installed for all window openings, the coal feed aperture, all instrumentation ports, and the gas sampling port. A plywood cap was

installed at the bottom of the combustion section to retain the wet ceramic and to hold the acrylic center core in place on the center line of the combustor. The combustor section was mounted on the combustor stand before the insulation liner was cast. The wet ceramic material (Kaocrete HDHS 98 RFT by Babcock and Wilcox) was then introduced at the top of the combustion section between the steel shell and the acrylic center core. This was done by shoveling in small batches of ceramic and tamping each batch to ensure filling the annular space completely and eliminating bubbles. The insulating liner required about 200 kg of the ceramic material. After casting, the liner was cured at room temperature for 48 hours.

After room temperature curing, all core materials were removed and special Kaocrete window core blocks were installed. A gas burner was installed in the bottom of the combustor as well as thermocouples to monitor the temperature at the bottom, center, and top of the combustor section. The curing process was started by heating the combustor (hottest position) to about 100 C and maintaining this temperature for 30 minutes. Then the heating was increased at the rate of about 100 C per hour until the maximum temperature anticipated during testing was reached (about 1000 C). After curing, the combustion section was allowed to cool naturally and the window cores were removed. Inspection of the insulating liner indicated that the casting and curing process had been successful.

#### Coal Bed and Bed Cooling System

After curing the insulating liner, the coal bed and bed cooling system were installed. It was also necessary to install the burner ring and igniter wire at this time. This was accomplished by first positioning the bed cooling coils about 10 cm above their normal position. The bed pivot rods were then introduced through the window and connected to the external control rods. The semi-circular coal bed sections were then clipped onto the bed pivot rods. After installation, the dumping action was successfully tested. The cooling coils were then lowered to their normal position (about 2.5 cm above the bed). After positioning the burner ring about 10 cm below the bed, and installing an igniter wire, the lower adapter elbow was lifted to the bottom flange of the combustor section and bolted in place. The lower adapter elbow was then bolted to the decoupler.

#### Coal Feed System

The mounting arrangement for the coal feed system was designed utilizing angle-iron sections. The required members were cut and welded or bolted in place and the correct positioning of the coal feed system was then determined. It was found necessary to enlarge the hole in the coal delivery

tube to fit properly with the auger tube. Even then a considerable gap remained, which was filled with a small section of pipe and epoxy. Due to proximity to the bottom combustor section flange, the auger tube could not be mounted at the 8 degree angle as originally planned, but at an angle a few degrees larger. This is not expected to significantly affect the coal feeding characteristics.

### Air, Water, and Gas Systems

The air, water, and natural gas systems were next installed. The air supply system is shown in Figure 2. This system supplies the main combustion air and also auxiliary air for either the limestone injection system or the secondary combustion air. The water system is shown in Figure 3. This system supplies cooling water to the upper and lower bed cooling stages and the coal delivery tube. The natural gas system is shown in Figure 4. This system supplies natural gas or propane to the igniter/preheater system.

In the air system (Figure 2), air from the building 850 kPa (125 psig) air supply passes through a pressure regulator to a 3.8 cm diameter flexible hose (rated at 1030 kPa) which is connected to a control valve on the control panel. The flowrate into the combustor (through the decoupler) is monitored on a rotameter. The line from the rotameter is split into primary and secondary lines, each with a control valve. The primary line is connected to the decoupler by a 3.8 cm diameter flexible hose. The secondary air system has not been installed at this time, so this valve remains closed.

In the water system (Figure 3), 1.27 cm diameter copper tubing connects the domestic water supply to a shut-off valve on the control panel. Copper tubing of the same diameter leads from the valve to a three-way branch located on the combustor frame. Here 0.64 cm diameter copper tubing provides water to the coal delivery tube, the lower coal bed cooling stage, and the upper coal bed cooling stage. The coal bed cooling stages each have a control valve. The water leaving the coal delivery tube and coal bed stages passes through 0.64 cm diameter plastic tubes which feed into a 1.27 cm diameter drain line.

In the gas system (Figure 4), natural gas (or propane) passes from the supply line through 1.27 cm diameter copper tubing to a shut-off valve on the control panel. This is followed by a solenoid valve, a control valve, and a rotameter. The solenoid valve is controlled by an ultraviolet flame detector mounted outside the lower combustor window. The solenoid valve automatically shuts off the flow of gas to the combustor if the flame detector does not sense a flame in the combustor. An "override" system

allows the solenoid valve to be opened, independently of the flame detector, to permit igniting the burner. The control valve is used to adjust the flow rate as measured by the rotameter. The gas then flows through a 0.64 cm diameter copper line which is connected to the stainless steel burner ring. The gas burns as a diffusion flame in the air stream supplied to the combustor. The air/fuel ratio is controlled by adjusting the air and gas flow rates to the combustor. The gas is ignited by a spark ignition system using a 10 kV AC power supply. The switches controlling the spark ignition system are located on the main control panel.

### Instrumentation

Instrumentation for steady temperature measurements and acoustic pressure measurements were installed during the quarter.

Three thermocouples were installed to measure temperature at the bed level, the middle level, and the top (exhaust) level. These were Type K (chromel-alumel) with 1.6 mm diameter Inconel sheaths. The thermocouples are connected to a multichannel sequential switching device which is connected to a digital temperature readout. Eight additional Type K thermocouples were ordered for later installation at intermediate positions.

A low impedance piezoelectric pressure transducer (Kistler Model 211B5) was installed in the combustor to measure the dynamic pressure amplitude or sound pressure level during pulsating operation. The transducer was installed at the middle level where the pressure amplitude is the greatest. To protect the transducer from the high temperature environment, the transducer was located in the side branch of a tee fitting connected to the combustor by a length of 0.64 cm diameter stainless steel tubing. The opposite end of the tee was connected to a 10 m long coiled section of soft plastic tubing to prevent acoustic resonances from occurring in the stainless steel tubing (i.e. by damping out reflections from the open end). The acoustic losses in the stainless steel tubing were determined to be about 2 dB, which are taken into account in the transducer calibration procedures. The output from the transducer is amplified and measured on a voltmeter and frequency counter for determination of the amplitude and frequency of the pressure oscillations, respectively. The transducer output is also displayed on an oscilloscope for general observation of the wave shape.

### Gas Analysis System

The gas sampling and analysis system was installed for the purpose of determining the composition of the exhaust gases. The exhaust gases are sampled through a probe

installed at the upper end of the insulated combustion section. The exhaust gases are transferred through a heated stainless steel tube to the exhaust gas analyzer system. The concentrations of five chemical species in the exhaust gases are determined by the analyzer. The concentrations of carbon monoxide, carbon dioxide, and sulfur dioxide are determined by means of infrared analyzers. A paramagnetic analyzer is used to determine the oxygen concentration, while the concentration of nitrogen oxides is determined by a chemiluminescent analyzer.

#### PRELIMINARY TESTS

After assembly of the Rijke tube pulse combustor and the auxiliary systems, preliminary tests were conducted. These tests, which were performed near the end of the report period, used natural gas as the fuel. The objective of these tests was to determine under what conditions pulsations could be driven with the gas burner.

In the first test, the burner was ignited in a position about 10 cm below the coal bed. The natural gas valve was fully open and the air flow rate was about 21 standard liters per second. No pulsations were observed in this configuration. Next the burner was raised to about 3.8 cm below the bed, and the air flow rate was increased. Pulsations were first noted when the air flow rate exceeded 28 liters/second, and they increased in amplitude as the air flow rate was increased. The maximum amplitude was about 142 dB at a flow rate between 38 and 40 liters/second. For flow rates above 45 liters/second the amplitude had decreased considerably, and at 52 liters/second pulsations were negligible. At the maximum flow rate the flames were about to blow off the burner. A plot of pulsation amplitude as a function of air flow rate is shown in Figure 5.

The pressure signals on the oscilloscope appeared sinusoidal with a frequency of about 70 Hz as obtained by the frequency counter. The theoretical frequency for air at room temperature for this combustor is about 57 Hz, while for air heated to about 150 C it is 68 Hz, which is consistent with the measured frequency.

The pulsations had a strong effect on the characteristics of the burner flames. In the absence of pulsations or at low amplitudes, the burner flames were yellow and extended through the coal bed grid. During pulsating operation the flames were mostly blue (with a little yellow) and they exhibited a rapid fluttering motion. Also the flames were shorter during pulsating operation and they did not extend above the coal bed.

The burner height had a strong effect on the pulsations. If the burner was raised about 0.6 cm or lowered

about 1.3 cm the pulsations stopped (for optimum air flow rate).

These tests with natural gas indicate that although pulsations can be driven in this combustor with gas alone, the amplitude is rather low (140 dB). Previous experience with coal burning pulse combustors and gasifiers indicate that much higher amplitudes were obtained (160-170 dB). The natural gas flow rate was limited by the low supply pressure, which limited the amount of energy available to drive pulsations. Therefore further tests are planned using propane fuel for which the supply pressure is much higher and which has a higher heating value than natural gas.

An additional test was conducted using coal to determine if higher amplitude pulsations could be driven. The only coal available at the time was lignite left over from an earlier project. This coal has a high moisture and ash content and is thus unsuitable to burn in this combustor. Nevertheless, higher amplitudes were achieved using this coal than with gas alone. At one point in this test the amplitude reached 158 dB. However pulsating combustion was difficult to maintain with this coal due to ash and clinker build-up on the bed and particularly between the water cooling coils.

#### FUTURE WORK

The following tasks are expected to be accomplished during the next quarter of this project: (1) procurement of coal, (2) tests with propane, (3) establishment of the operating characteristics with coal, and (4) completion of the installation and testing of the limestone system.

Approximately one metric ton of coal will be obtained from Georgia Power Company's Plant McDonough to use as fuel during this research project. The coal will be obtained from a single trainload to ensure uniform composition. Proximate and ultimate analysis of the coal will be obtained.

A permanent propane system will be installed in order to increase the heating available for igniting the coal and preheating the combustor. Tests with propane alone will be conducted to establish the pulsation limits in terms of air/fuel ratio. Also the flue gas composition will be determined ( $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{NO}_x$ ,  $\text{SO}_2$ ).

A series of tests will be conducted to establish the operating characteristics of the combustor with coal obtained from Georgia Power Company. First the coal feed system will be calibrated to determine the feed rate (in g/min) as a function of the rotational speed of the auger (RPM). An electronic tachometer will be installed in order to accurately measure the auger rotational speed. A series

of tests will be conducted for a fixed feed rate (to be determined after calibration) and for different air flow rates. These tests are expected to establish the pulsation limits (air/fuel ratios) of the combustor for this feed rate. For pulsating operation, frequencies and amplitudes will be obtained. Combustor temperatures and flue gas compositions will be obtained for both pulsating and non-pulsating operating conditions.

To complete the installation of the limestone system, tubing and fittings will be obtained, as well as a pressure regulator and rotameter. The pulverized limestone entrainment system (hopper, auger and venturi) will be assembled and installed on top of the combustor frame. After obtaining a supply of pulverized limestone, the limestone injection system will be tested and calibrated.

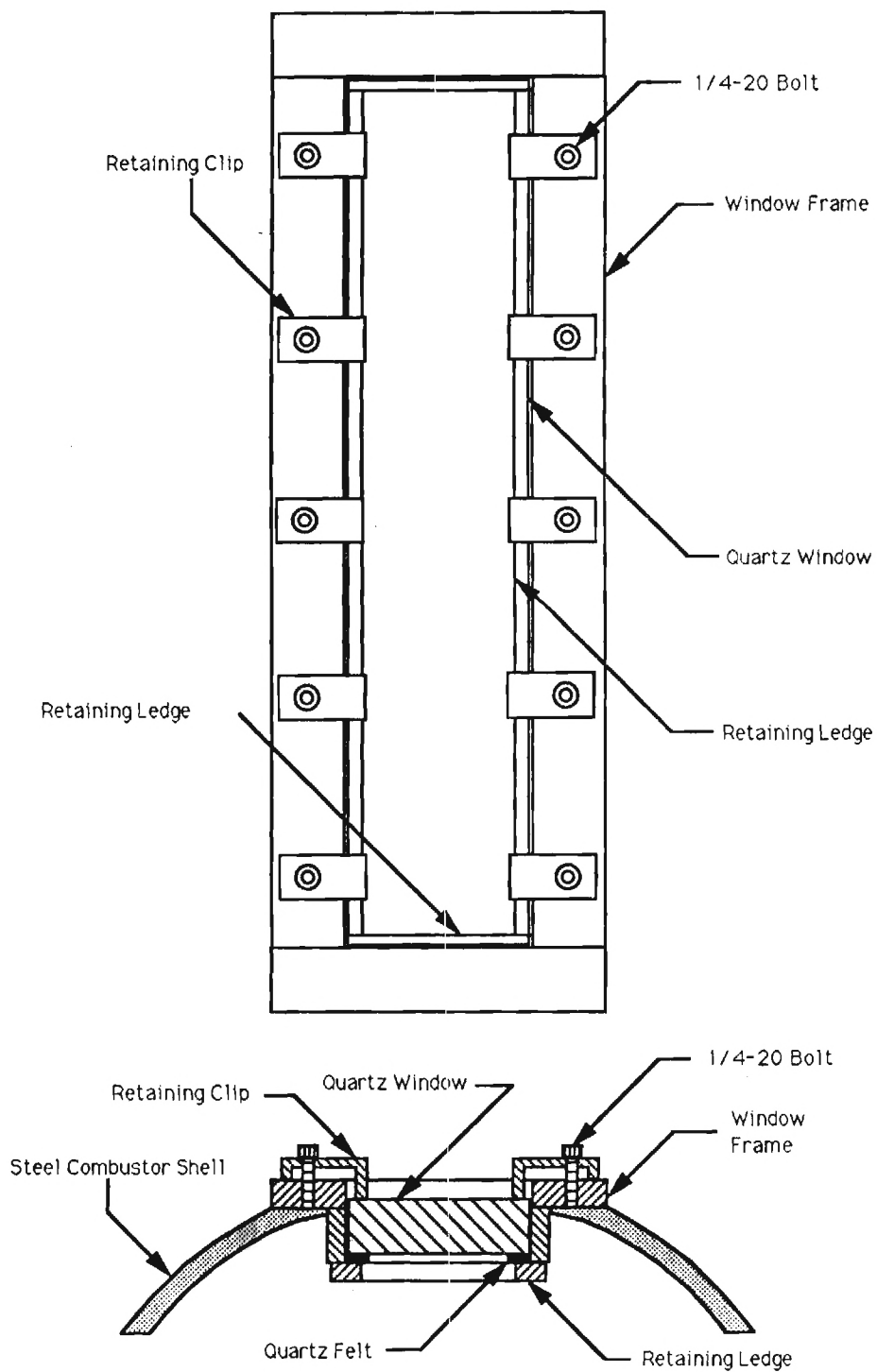


Figure 1. Combustor Observation Window

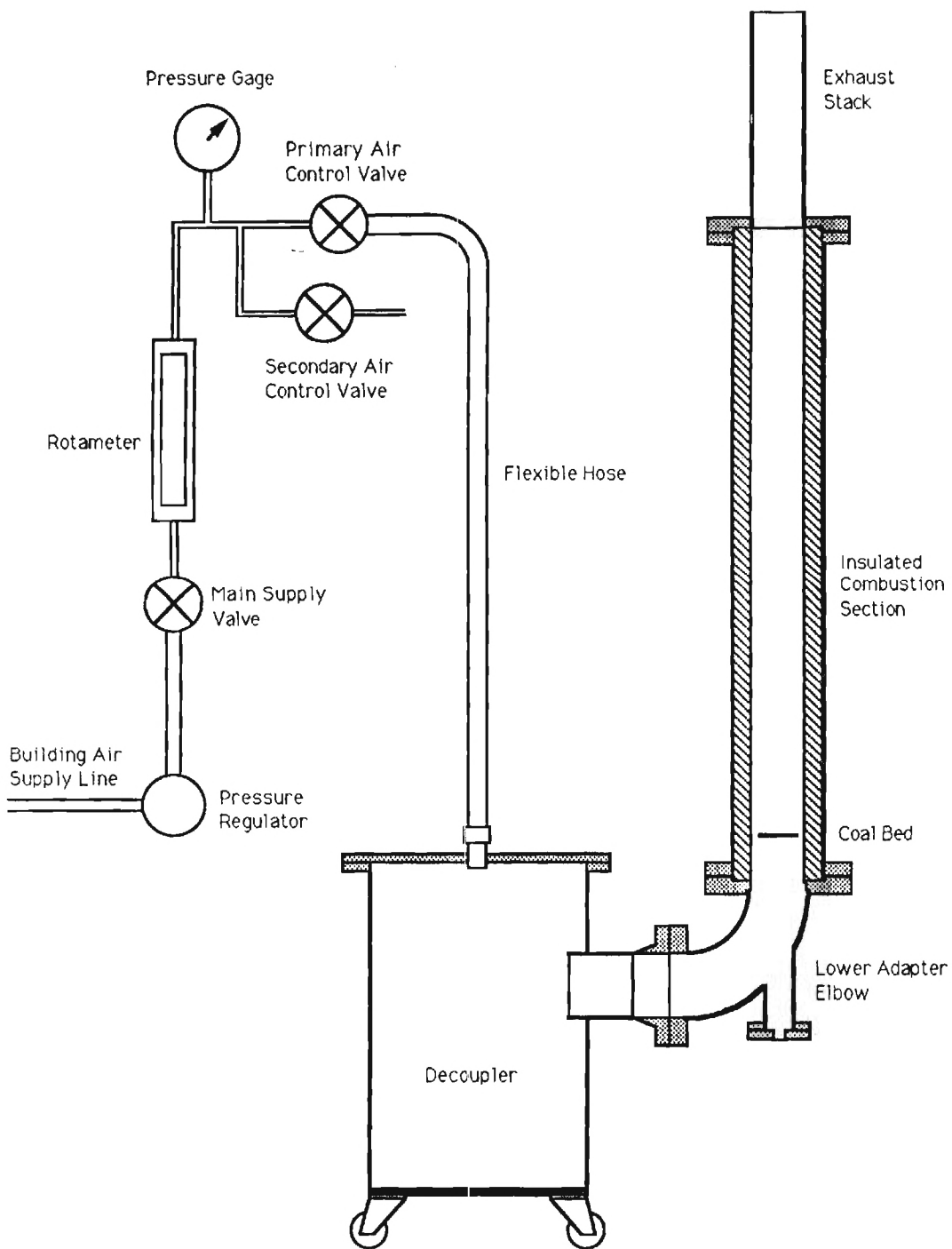


Figure 2. Rijke Pulse Combustor Air System

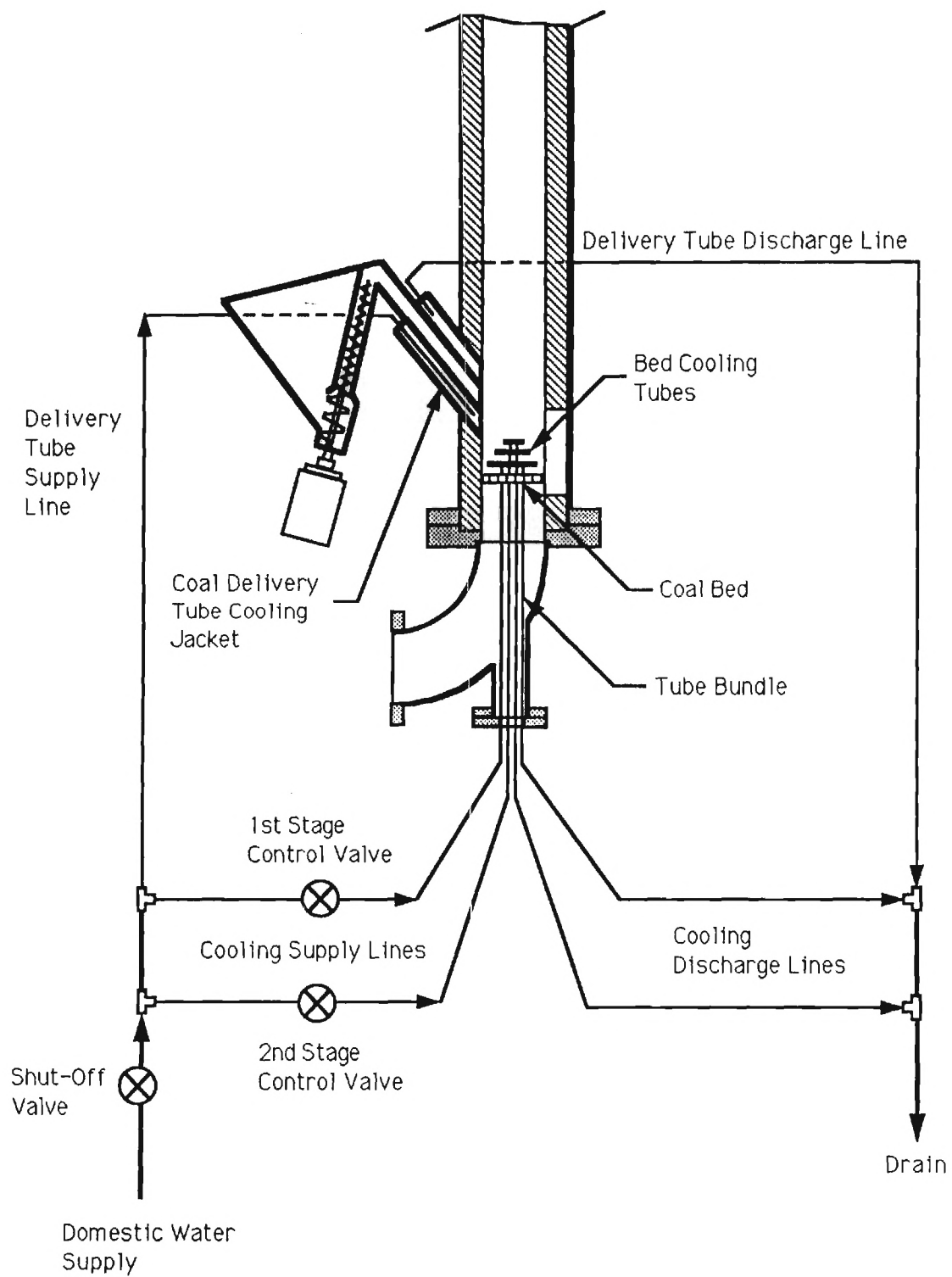


Figure 3. Rijke Combustor Water Cooling System

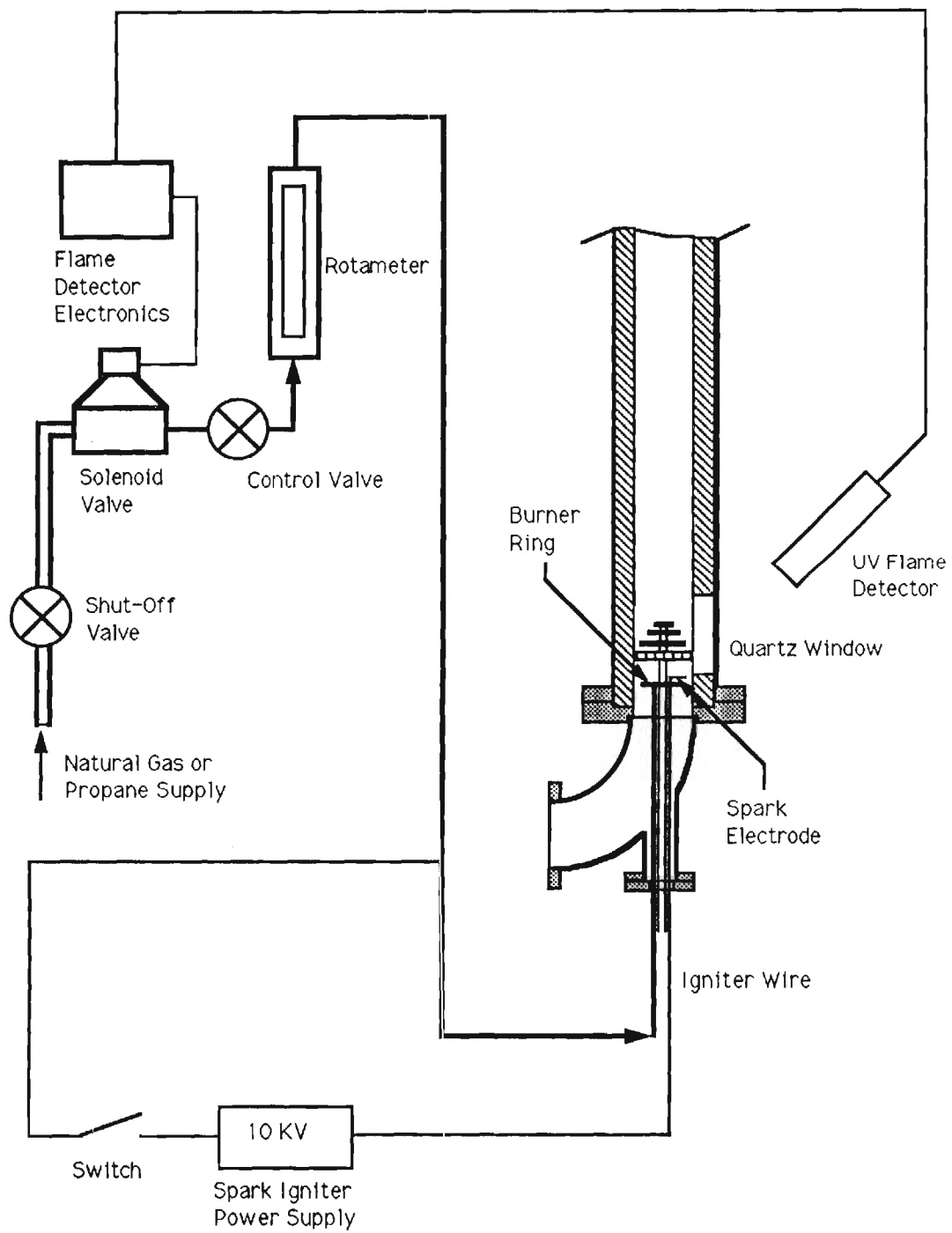


Figure 4. Rijke Combustor Ignition/Preheating System

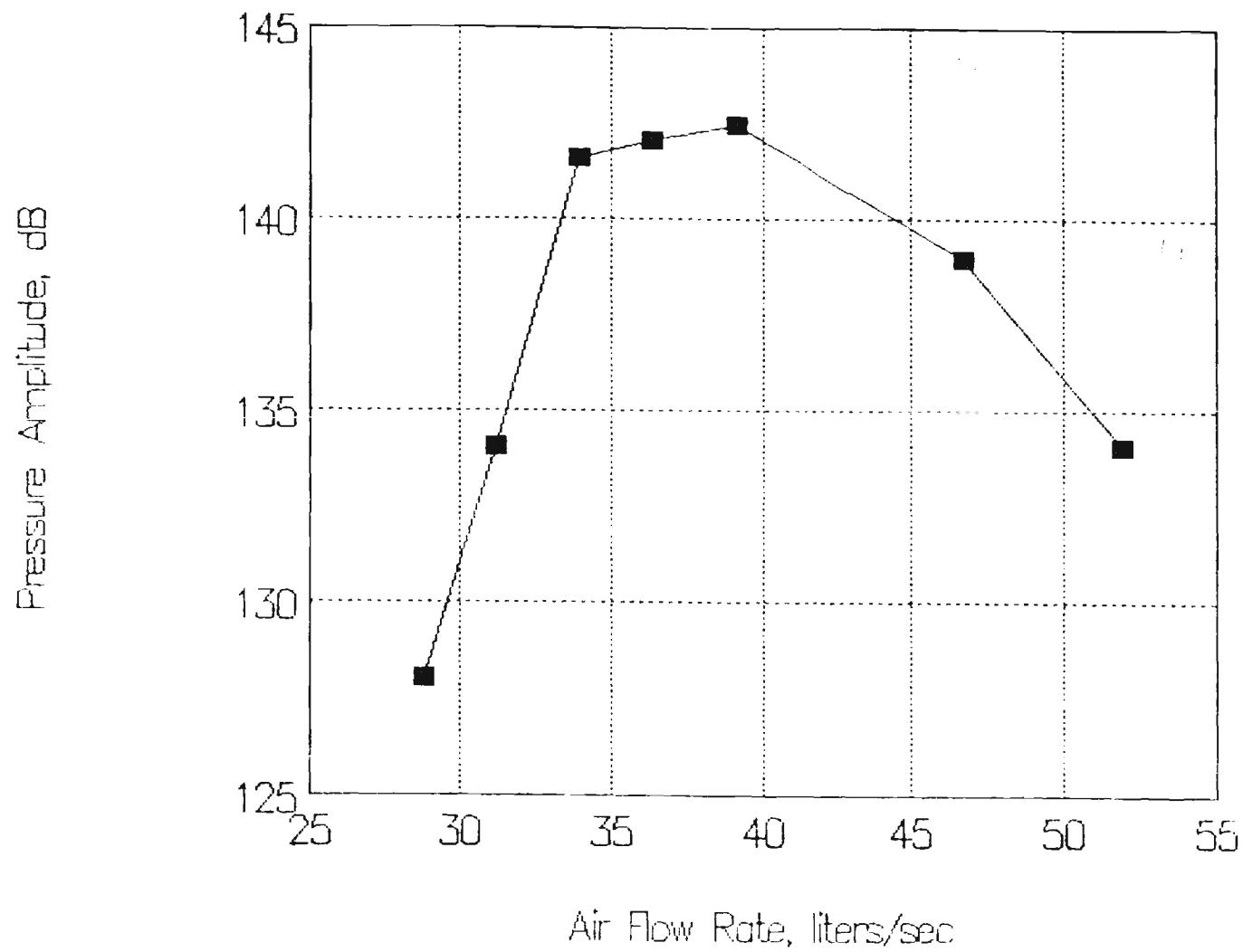


Figure 5. Sound Pressure Level vs Air Flow Rate for Rijke Tube Pulsations with Natural Gas.

REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
FROM COAL BURNING PULSE COMBUSTORS

Quarterly Technical Progress Report  
for the Period July 1, 1989 - September 30, 1989

By

E. A. Powell and B. T. Zinn

October 1989

Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy  
Office of Fossil Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania 15236

By

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UNITED STATES DEPARTMENT OF ENERGY

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COAL PULSE COMBUSTION RESEARCH

Quarterly Technical Progress Report for the  
Period July 1, 1989 - September 30, 1989

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October 1989

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United States Department of Energy  
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Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

## ABSTRACT

Work accomplished during the fourth quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of the nitrogen oxides and sulfur dioxide emissions from Rijke type pulse combustors by using combustion staging and limestone addition. During this quarter about five metric tons of bituminous coal needed for the combustion experiments was obtained from Georgia Power Company, and proximate and ultimate analyses of this coal were obtained. Modifications were made on the combustor to provide for easy removal of ash, to provide a more uniform flow of air through the coal bed, and to provide an access port in the exhaust stack needed for installing the limestone injection system. The sulfur dioxide analyzer was found to be giving false readings due to a combination of sulfur contamination and moisture in the sampling system. A new element for the sample gas dryer was ordered. A series of tests of the Rijke combustor using propane fuel (without coal) was conducted. Measurements of sound pressure level, frequency, gas composition, and temperatures were made during pulsating operation over a range of fuel flow rates and air/fuel ratios. Measured carbon dioxide and oxygen concentrations were in good agreement with theoretical calculations. Nitrogen oxide concentrations ranged from 70 to 90 ppm on a zero percent oxygen basis. Finally a series of tests with coal were conducted, which established a reliable procedure for initiating pulsating combustion of the coal. In a typical test run, the coal feed rate was about 80 g/min and pulsating combustion (with amplitudes up to 160 dB) was maintained for about 15 minutes under stoichiometric conditions.

## INTRODUCTION

The following report summarizes the work done under DOE Grant No. DE-FG22-88PC88918 during the period July 1, 1989 through September 30, 1989. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

The following work will be described in this report: (1) the procurement and analysis of the coal to be used in this investigation, (2) several modifications of the Rijke tube combustor found necessary during preliminary testing, (3) installation and checkout of instrumentation, (4) tests conducted using propane fuel without coal, and (5) tests conducted with coal to establish basic operating parameters and conditions. The report will conclude with projected work to be accomplished during the next quarter.

## PROCUREMENT OF COAL

### Description

The coal to be burned in the Rijke pulse combustor was obtained at no cost from Georgia Power Company's Plant McDonough, which is located about 10 miles from Georgia Tech. Twelve 55-gallon drums of bituminous coal were obtained from Plant McDonough on August 23. This coal was obtained from a large pile which had recently been delivered from a single trainload. The coal as received had a wide range of particle sizes, from coal dust (less than 0.1 mm) to large lumps several centimeters across.

### Analysis of the Coal

A representative sample of the coal obtained from Plant McDonough was subjected to proximate and ultimate analysis. The proximate analysis was performed at the Central Test Laboratory of Georgia Power Company, while the ultimate analysis was performed by the General Test Laboratory of Alabama Power Company. These analyses were obtained at no cost to the project. The results of the analysis are presented in Table 1.

### Sizing of Coal

In order to obtain consistency in the size distribution of the coal lumps burned in this combustor, a large sieve was constructed for sizing the coal obtained from Georgia Power Company. This consists of a wooden frame with a hinged lid. The bottom of the frame holds a hardware cloth screen to retain coal particles larger than about 6 mm in diameter. A coarser screen on the lid retains coal lumps larger than

about 12 mm in diameter. The sieve fits over the top of an empty 55-gallon drum which catches the fine particles which fall through the lower screen. The coarser lumps are retained on the upper screen and are stored separately for later crushing. The particles between the screens are then transferred to drying boards and later stored for use in the combustor.

## MODIFICATIONS TO RIJKE COMBUSTOR

### Ash Removal

Before burning coal in the combustor, a provision for removing ash and unburned coal particles from the lower adapter elbow was needed. A hole was cut and a section of 11.4 cm O.D. steel pipe was welded to the bottom of the elbow adjacent to the flange as shown in Figure 1. This pipe was provided with a flange and cover plate. During combustor operation, ash and unburned coal accumulate in this trap which can be emptied periodically.

### Coal Retaining Barrier

Early tests with coal indicated that uniform flow of air through the coal bed is essential for maintaining pulsations. In the original window design a large gap between the forward edge of the bed and the quartz window allowed air to bypass the bed. Also it was found that coal tended to fall through this gap.

To eliminate these problems a coal retaining screen was installed as shown in Figure 2. The screen was made of the same stainless steel screen as the bed, and it formed a barrier to prevent coal from falling through the gap between the bed and the window. The screen was welded to a horizontal stainless steel plate which filled the space between the window and the bed to prevent the air flow from bypassing the bed. The coal retaining screen was mounted in two notches cut in the window frame at the bed level.

In subsequent tests with coal under pulsating conditions, the high temperatures in the bed resulted in partial melting and burnout of the screen. The screen was then replaced with a block of the same ceramic refractory material used to line the combustor.

### Modification of Upper Stack

In order to install the limestone injection system, a modification of the upper exhaust stack was made. This was necessary because the gas sampling probe extends across the center of the combustion tube and interferes with the originally planned axial injection tube. The modification involved putting an access port (11.4 cm O.D. pipe) near the lower end of the exhaust stack as shown in Figure 3. This allows installation of the limestone injection tube.

Furthermore, the sampling probe was moved from the upper end of the insulated combustion section to a position about 15 cm above the access port.

## INSTRUMENTATION

### Thermocouple Installation

Thermocouples were installed at eight stations above the coal bed at heights of 1.3, 10, 18, 30, 46, 76, 114, and 152 cm. These were Type K (chromel-alumel) thermocouples with 1.6 mm diameter Inconel sheaths. Each extended inward toward the axis to measure gas temperatures about 5 cm from the combustor wall. The thermocouple output voltages were amplified and input to the computerized data acquisition system.

### Gas Analysis System

During tests with propane fuel (no coal) to be described later, unexpectedly high concentrations of sulfur dioxide were measured. Since the propane contains negligible amounts of sulfur, contamination of the air supply was at first suspected. However, subsequent tests where room air was drawn through the sampling train into the SO<sub>2</sub> analyzer indicated SO<sub>2</sub> concentrations of about 400 ppm. Even in industrialized areas the ambient SO<sub>2</sub> concentrations are much smaller, only about 0.08 ppm. Tests were then conducted to determine if there was contamination in the sampling train, which consists of stainless steel sampling lines, a filter, a counterflow permeation type dryer, a diaphragm type vacuum pump, and the SO<sub>2</sub> analyzer (Beckman model 865). The results indicated possible contamination in the dryer and the pump. Furthermore the tests indicated that the dryer was ineffective in removing water vapor from the sampling stream. Since the infrared SO<sub>2</sub> analyzer responds also to water vapor, this appeared to be the source of the spurious readings. Attempts to clean the dryer failed to improve its performance, so the dryer was shipped to the manufacturer to have a new drying element installed. The dryer was shipped near the end of the quarter, and so the gas analysis system was not available for further tests with coal conducted late in the quarter.

## TESTS WITH PROPANE

A series of tests were conducted using propane fuel but without coal to establish the pulsating behavior of the combustor and to check out the instrumentation. In these tests the burner was located about 4.5 cm below the bed, and the bed cooling system was utilized at maximum water flow rate. The air supply pressure was regulated at 480 kPa (gage) just upstream of the flowmeter. The fuel supply

pressure varied according to the fuel flow rate; it was measured just upstream of the flowmeter and used to correct the flow rate. For these tests, five fuel flow rates were used - 64.3, 42.8, 25.5, 17.0, and 11.9 standard liters per minute (SLM). For each fuel flow rate, air flow rates were taken from just below onset of pulsations to flame blowoff or fullscale flowrate (2040 - 6630 SLM). Measurements were made of gas composition ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{SO}_2$ , and  $\text{NO}_x$ ), pulsation amplitude and frequency, and gas temperatures above the bed.

It was found that rather high air/fuel ratios were necessary to obtain pulsating combustion with propane fuel. Thus it was suspected that air velocity rather than stoichiometry is one of the important factors in determining the pulsating behavior. The other important factor is the energy release rate due to combustion, which is proportional to the fuel flow rate. A plot of pulsation amplitude (sound pressure level in dB) as a function of air velocity below the bed is shown in Figure 4 for the five energy release rates (16 - 88 kW). Two separate pulsating regimes were found. For high energy input (above 35 kW), the velocity needed for peak amplitude increases with increasing energy input (likewise the threshold velocity for pulsations increases). For this regime, the flame is mostly attached to the coal bed grid with only intermittent flames seen below the bed. The peak amplitudes lie between 156 and 158 dB with frequencies between 67 and 70 Hz. For lower energy input, the threshold was less well defined, the peak amplitude was lower (150 - 152 dB), the frequencies were lower (61 - 64 Hz), and velocities required for peak amplitude were higher (5 - 6 m/sec). Furthermore the flames remained attached to the burner ring and extended up through the bed.

In order to check out the gas analysis system, carbon dioxide and oxygen concentrations were measured and plotted as a function of stoichiometric air/fuel ratio. Theoretical concentrations were calculated assuming complete combustion of the propane to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . The experimental and theoretical  $\text{CO}_2$  concentrations are compared in Figure 5, while the  $\text{O}_2$  concentrations are shown in Figure 6. The agreement between the experimental data and theoretical calculations was fairly good, with the  $\text{CO}_2$  mole fractions lower than theoretical for the smaller air/fuel ratios (less than 6) and larger than theoretical for higher air/fuel ratios (greater than 7). The  $\text{O}_2$  mole fractions exhibited the opposite trend (above theoretical for smaller air/fuel ratios and below theoretical for higher air/fuel ratios). These trends indicate that part of the discrepancy may be due to errors in obtaining the air/fuel ratios (most likely in flow rate determinations). Thus the flow meters used will need to be recalibrated.

The measured  $\text{NO}_x$  concentrations exhibited an inverse dependence on air/fuel ratio primarily due to the dilution effect of the excess air. The  $\text{NO}_x$  mole fractions varied from about 43 ppm to about 4 ppm over the range of air/fuel ratios investigated. To remove the dilution effect, the  $\text{NO}_x$  mole fractions were reduced to a zero percent  $\text{O}_2$  basis. The reduced mole fractions are shown in Figure 7. Two clusters of data points were obtained. For the higher fuel flow rates, the reduced  $\text{NO}_x$  concentrations fell around 70 ppm, while for the lower fuel flow rates about 90 ppm was obtained.

As mentioned above,  $\text{SO}_2$  concentrations measured during these tests were suspiciously high, ranging from 170 to 420 ppm. Since negligible  $\text{SO}_2$  concentrations are expected when burning propane fuel in room air, a problem with the gas analysis system (contamination or interference) is suspected.

Carbon monoxide concentrations were also measured during these tests. For the each fuel flow rate, CO mole fractions unexpectedly increased with increasing air/fuel ratio. For the highest fuel flow rate (64.3 SLM) CO mole fractions ranged from about 100 to 700 ppm, while for the lowest fuel flow rate (11.9 SLM) the range was much smaller (100 - 200 ppm). These results are open to question, since moisture (which was not completely removed by the dryer) in the combustion products can give a false reading of CO in the infrared analyzer.

Temperature measurements were made while burning propane fuel under pulsating conditions. For the highest fuel flow rate, the peak temperature occurred about 18 cm above the bed. Peak temperatures decreased with increasing air/fuel ratio as expected, ranging from about 1300 C to about 1000 C. For lower fuel flow rates and higher air/fuel ratios, the peak temperature shifted to the lowest station (just above the bed). For the two lowest fuel flow rates, maximum temperatures ranged from about 900 C to about 500 C. Ignoring anomalously low readings at the second station, temperature decreased smoothly with height above the bed, which is expected due to heat losses through the combustor walls.

#### TESTS WITH COAL

During the last few weeks of the report period, several tests of the Rijke combustor with the Georgia Power coal were conducted. The purpose of these tests was to determine the procedures necessary for the establishment of pulsating operation with coal for long periods of time (15 minutes or longer). In the course of these tests several difficulties were encountered. The problem with the gap between the bed and the window was successfully corrected using the coal

retaining barrier described above. A major problem was the tendency of the coal to agglomerate on the bed and between the tiers of the bed cooling system. Also the heat removal by the cooling system tended to damp or reduce the amplitude of the pulsations. The combustor could not be operated without water flow to the cooling system without burning out the cooling coils. Eventually the cooling coils were removed in order to eliminate the agglomeration and heat removal problems. For the investigation of  $\text{NO}_x$  suppression methods, the cooling coils are not needed. However they may be needed for temperature control when sorbents are used for  $\text{SO}_2$  reduction.

In tests conducted without the cooling coils and with the coal retaining barrier mounted in the viewing window, pulsations were successfully initiated and maintained for periods of about 15 minutes. These tests were conducted according to the following procedure. Beginning with an empty bed, the combustor was first preheated with propane for about 10 minutes under non-pulsating conditions. During the preheat phase the propane flow rate was about 25 SLM and the air flow rate was about 1020 SLM. Next the coal feed was started at the desired rate (60-100 g/min) with the propane still on. After about one or two minutes, the coal was burning vigorously (non-pulsating), and the propane was shut off. At this point the stoichiometric air/fuel ratio for the coal was about 1.25, and pulsations were absent. The air flow was then reduced to stoichiometric conditions, which then initiated pulsations. The combustor would then operate for several minutes at fairly steady amplitude (up to 160 dB) until bed nonuniformities and large agglomerates developed and the pulsations would die out. Stirring the bed with 3 mm diameter rods inserted through the thermocouple ports often renewed the pulsations. Eventually ash accumulation and agglomeration prevented continued pulsating operation and the test was terminated.

#### FUTURE WORK

During the next quarter, several modifications to the coal bed will be made to improve bed uniformity and extend running time.

The refurbished dryer will be installed in the sampling train, and tests will be conducted to determine if the spurious  $\text{SO}_2$  readings have been eliminated.

A systematic study will be conducted to determine the baseline operation (without  $\text{NO}_x$  or  $\text{SO}_2$  reduction measures). Several coal feed rates will be selected, and for each coal feed rate, tests will be conducted for several air/fuel ratios. For each test, gas composition, pulsation amplitude and frequency, and temperatures will be measured. Also

combustion efficiencies will be calculated based on the measurements.

The axial injection system for secondary air, secondary fuel or limestone will be installed.

The investigation of  $\text{NO}_x$  reduction techniques will be initiated. Both air staging and fuel staging will be studied. In air staging, the coal is burned under substoichiometric conditions and secondary air is injected some distance above the primary combustion zone to complete the combustion process. In fuel staging, the coal is burned with excess air and additional fuel is injected in the secondary combustion zone. Here propane will be used as the secondary fuel. The effect of primary and secondary stoichiometry and injection height above the coal bed will be studied.

Table 1. Coal Analysis

## PROXIMATE ANALYSIS

Analysis	As Determined	As Received	Dry
Moisture	2.05	5.60	-
Volatiles	33.19	31.98	33.88
Ash	11.08	10.68	11.31
Fixed Carbon	53.68	51.74	54.81
Sulfur	1.31	1.26	1.33
BTU/lb	12931	12436	13174

60-Mesh Moisture: 1.84%

8-Mesh Moisture: 1.63%

## ULTIMATE ANALYSIS

Analysis	As Determined	Dry
Carbon	72.20	73.85
Hydrogen	5.09	4.95
Nitrogen	1.48	1.51
Sulfur	1.31	1.33
Oxygen	6.60	7.03
Ash	11.08	11.33
Moisture (60 mesh)	2.24	-

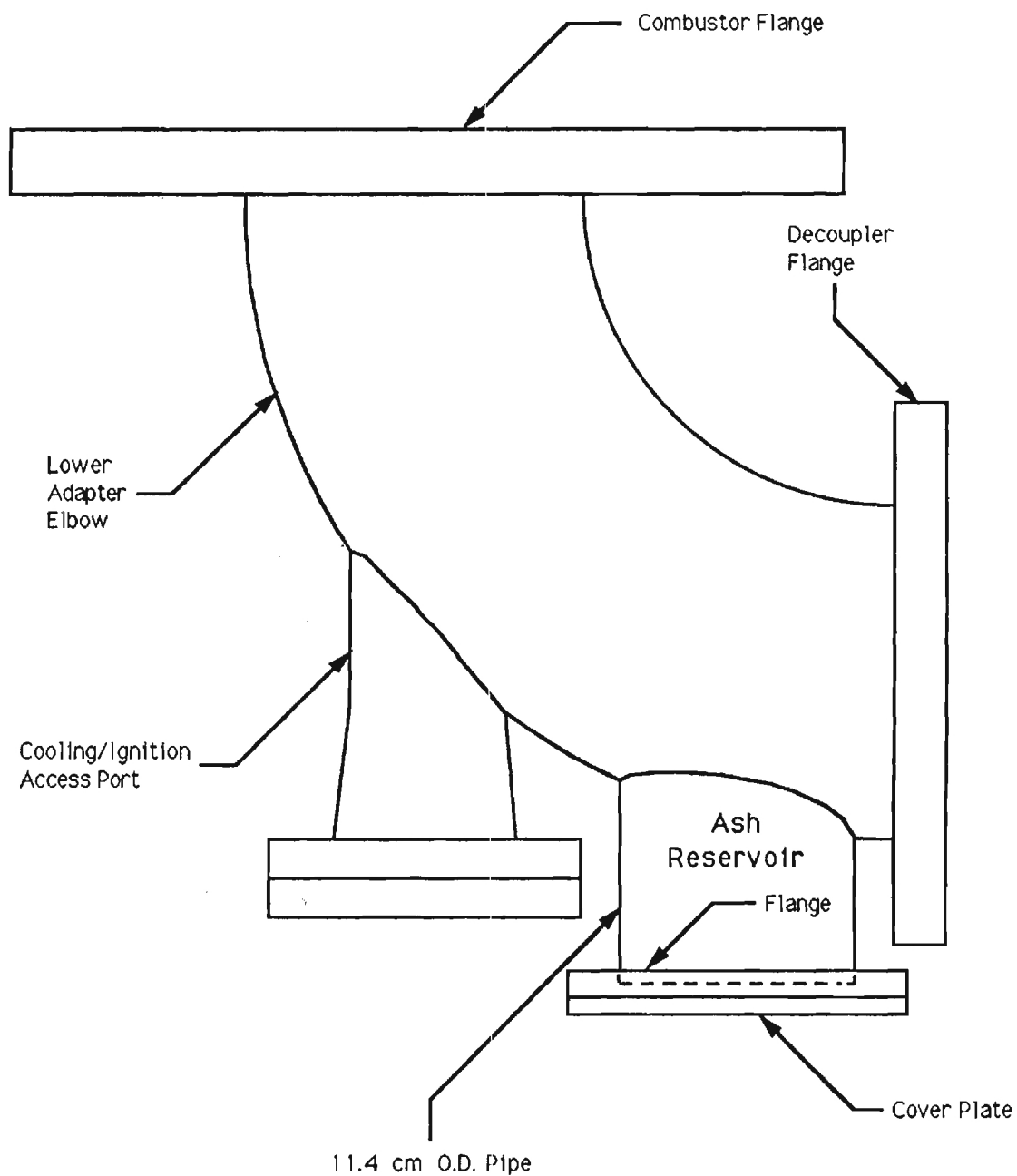
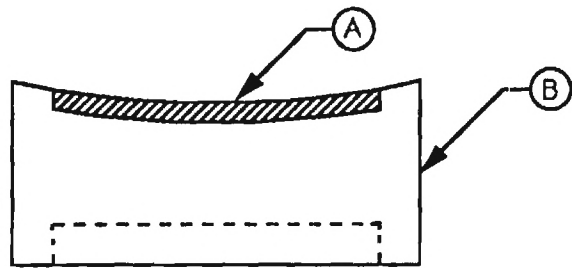
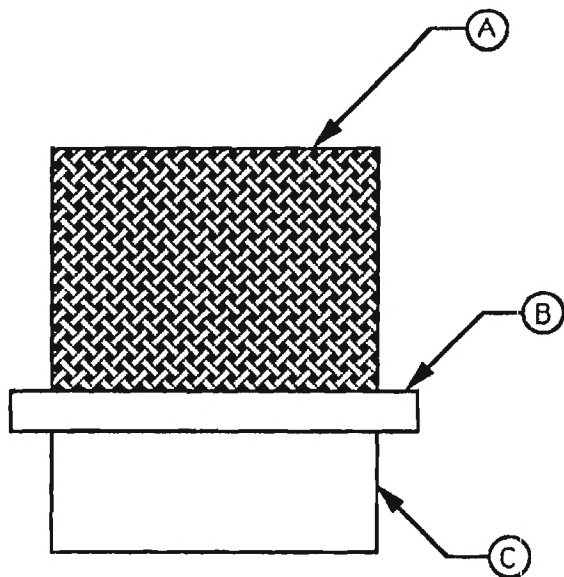


Figure 1. Modification of Lower Adapter Elbow for Removal of Accumulated Ash

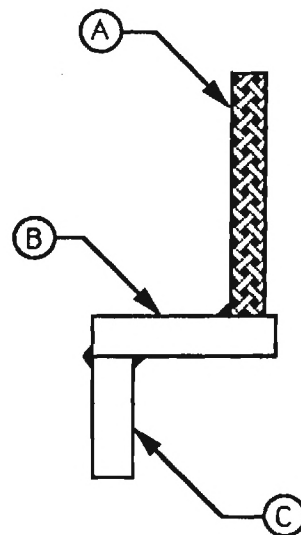


Top View

- (A) Screen
- (B) Shield
- (C) Support



Front View



Side View

Weld as  
Shown

Figure 2. Coal Retaining Screen

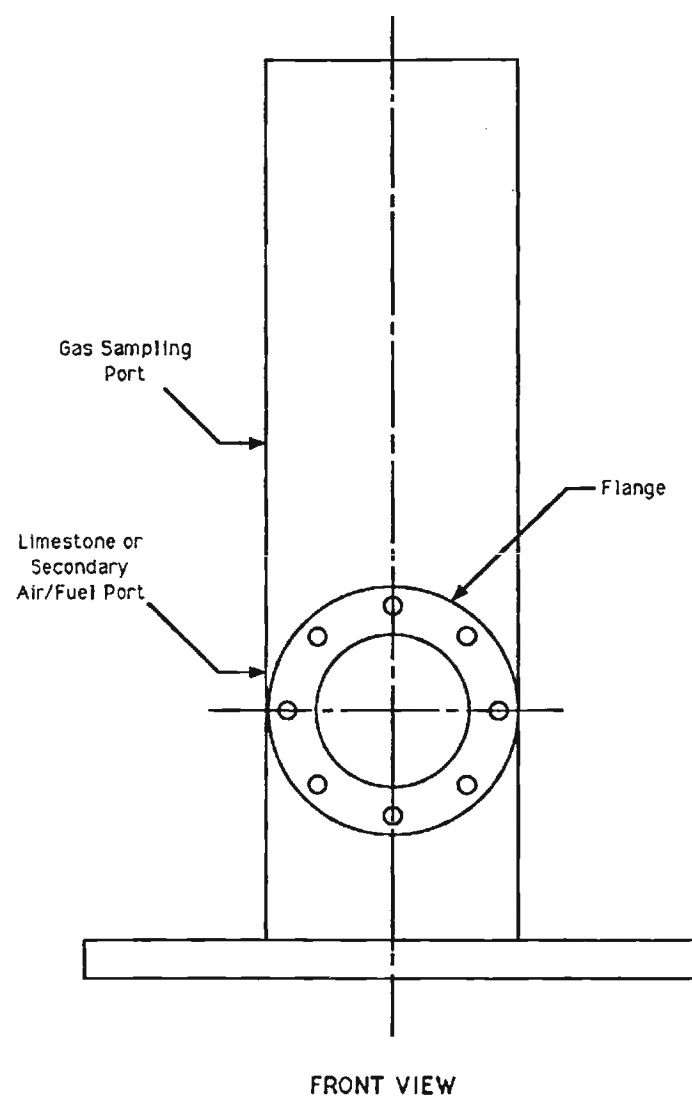
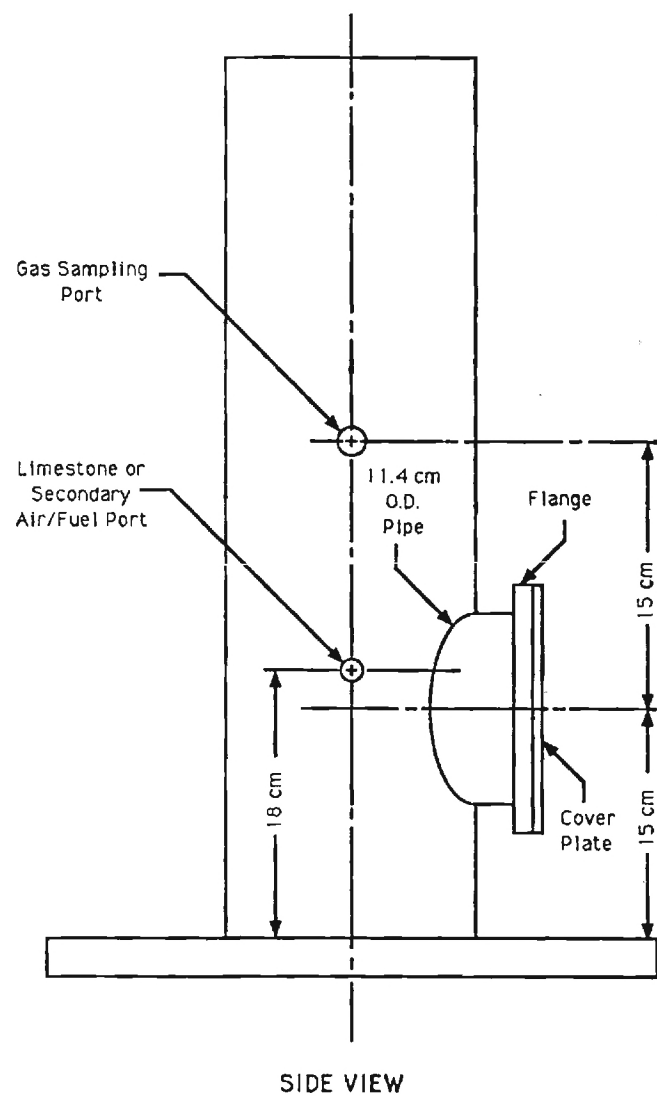


Figure 3. Exhaust Stack Modification to Provide Access Port

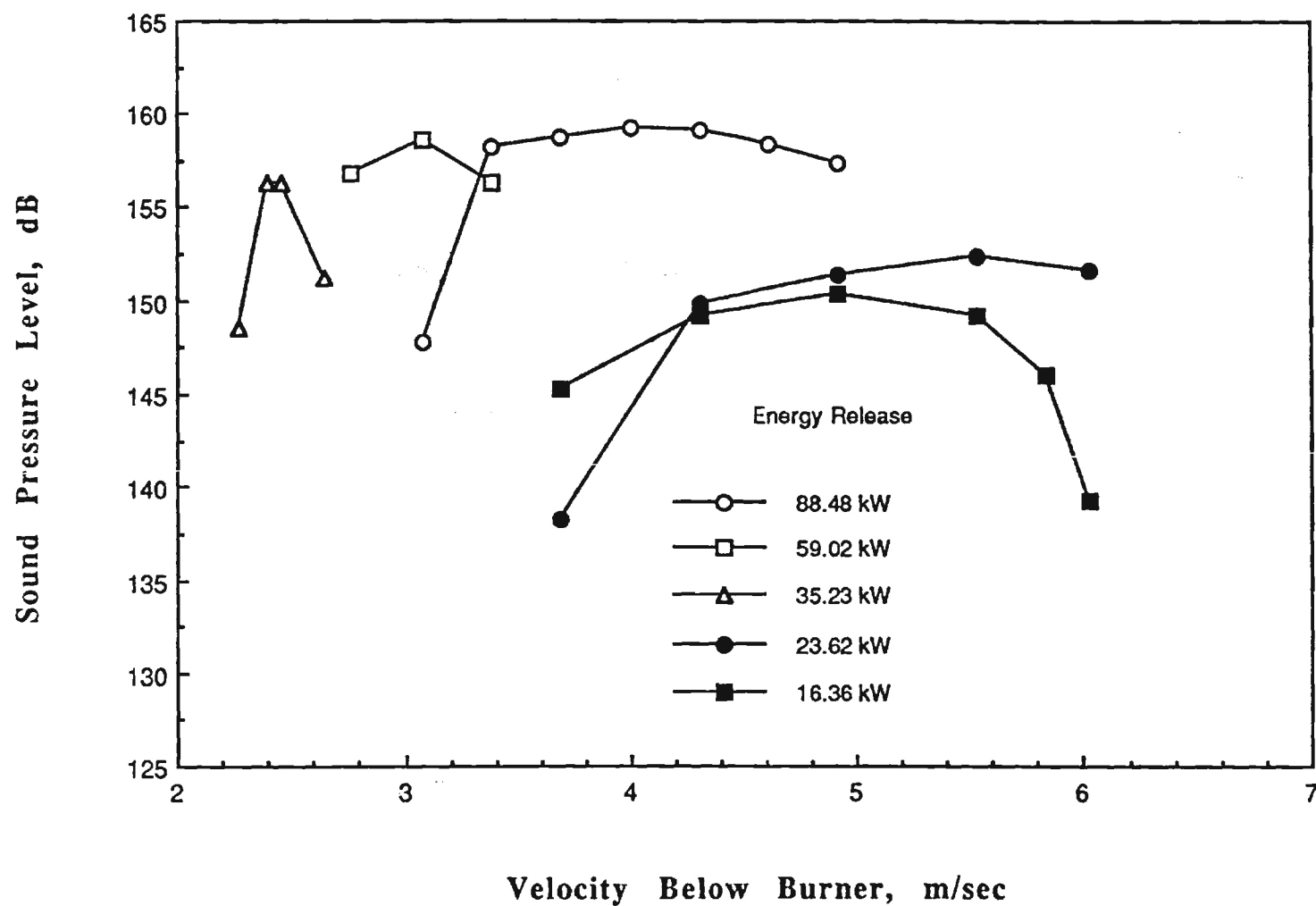


Figure 4. Pulsation Amplitude vs Air Velocity for Propane Combustion in Rijke Tube.

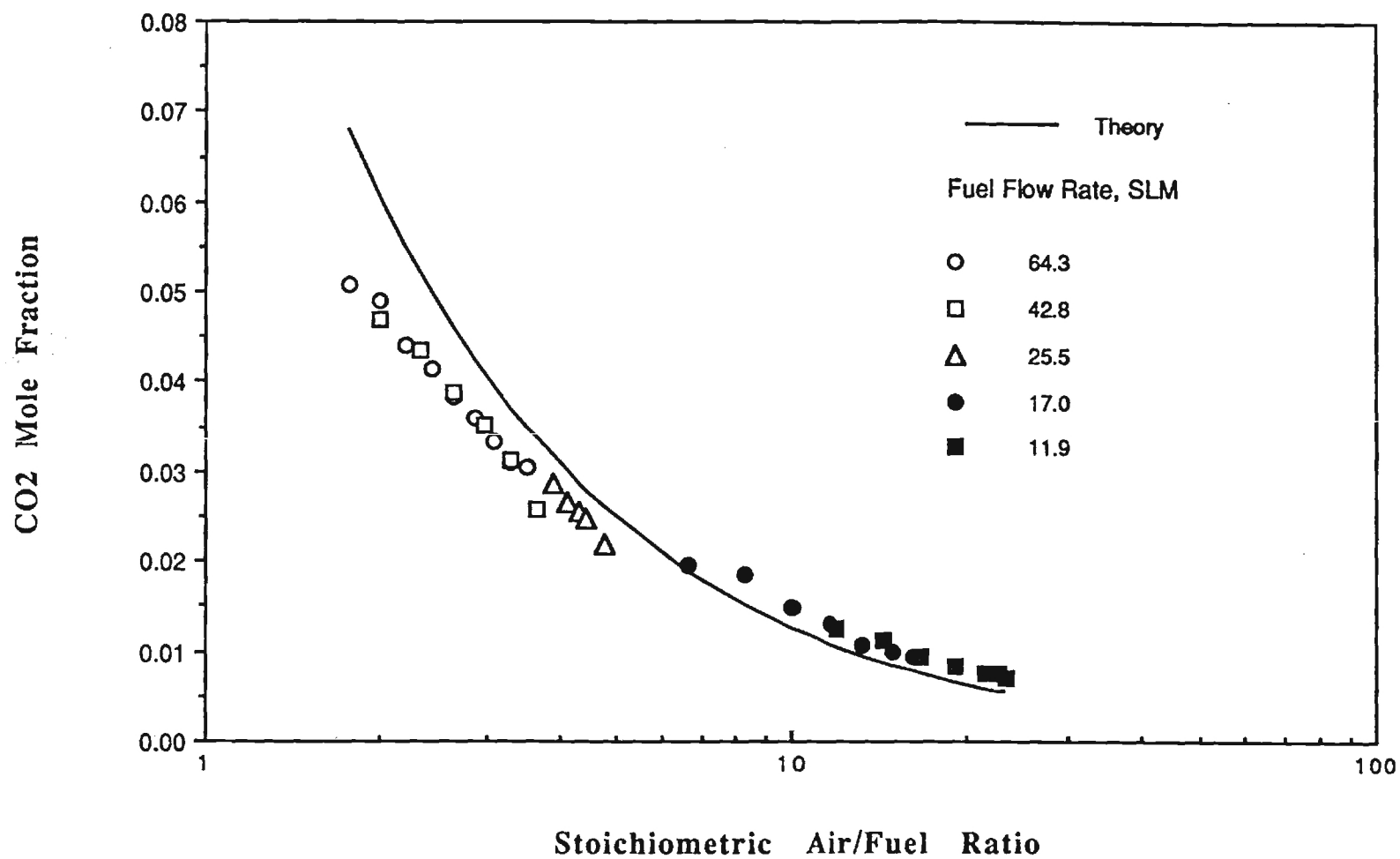


Figure 5. Carbon Dioxide Concentration vs Air /Fuel Ratio for Propane Combustion in Rijke Tube.

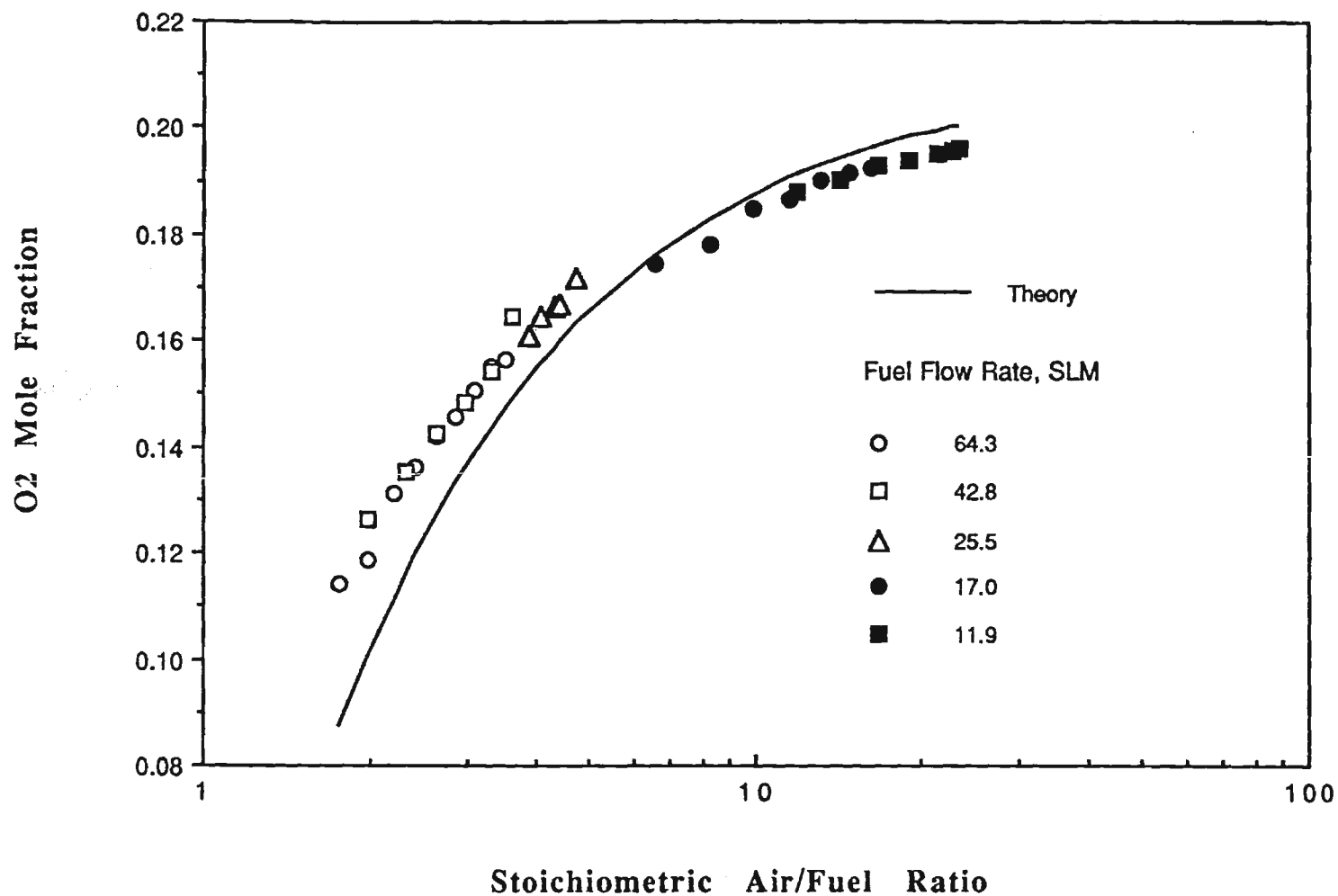


Figure 6. Oxygen Concentration vs Air/Fuel Ratio for Propane Combustion in Rijke Tube.

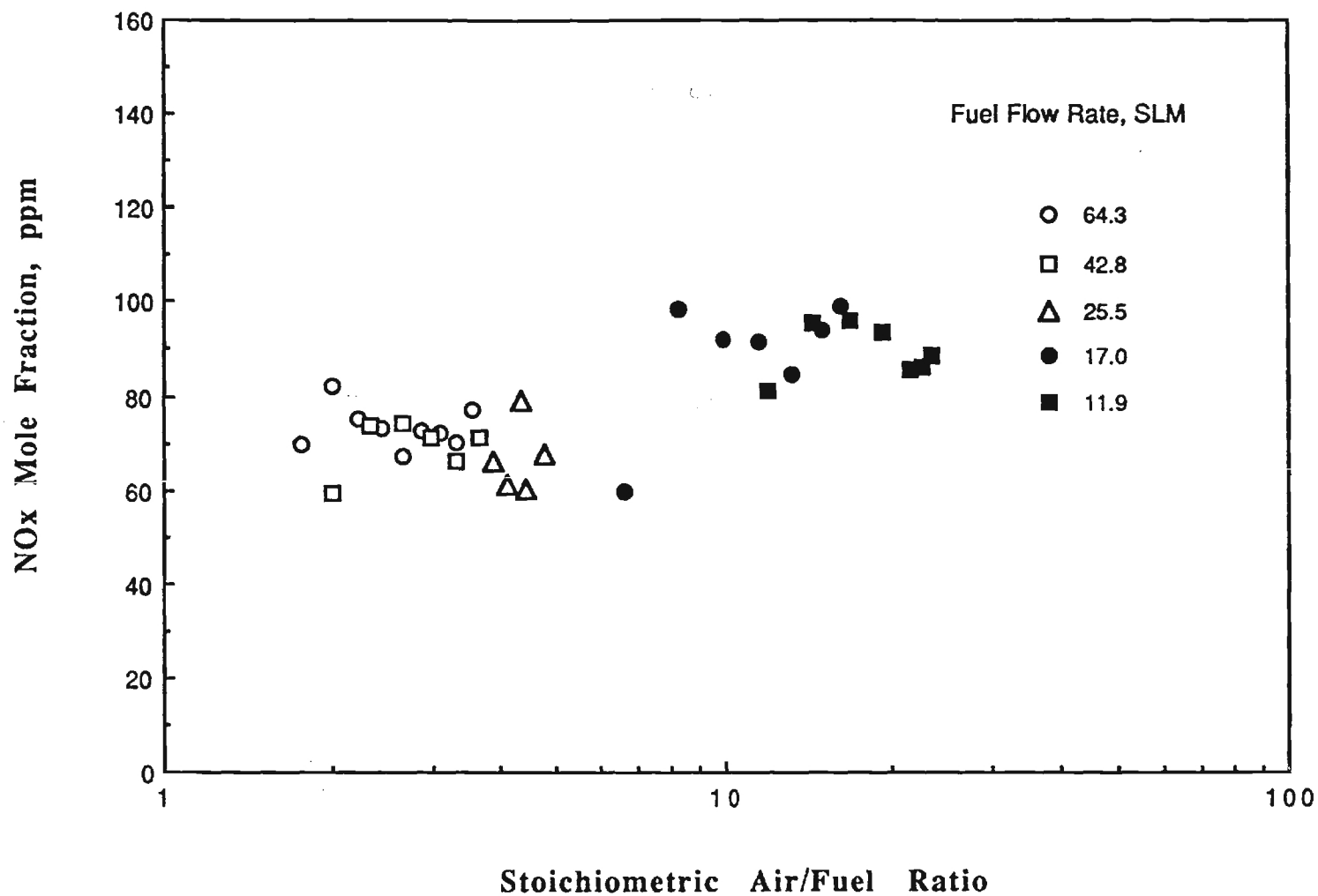


Figure 7. Nitrogen Oxides Concentration vs Air/Fuel Ratio for Propane Combustion in Rijke Tube.

REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
FROM COAL BURNING PULSE COMBUSTORS

Quarterly Technical Progress Report  
for the Period October 1, 1989 - December 31, 1989

By

E. A. Powell and B. T. Zinn

January 1990

Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy  
Office of Fossil Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania 15236

By

School of Aerospace Engineering  
Georgia Tech Research Corporation  
Georgia Institute of Technology  
Atlanta, GA 30332

TECHNICAL INFORMATION CENTER  
OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION  
UNITED STATES DEPARTMENT OF ENERGY

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COAL PULSE COMBUSTION RESEARCH

Quarterly Technical Progress Report for the  
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Prepared by

E. A. Powell and B. T. Zinn

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January 1990

Technical Project Officer - Perry Bergman

Prepared for

United States Department of Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

## ABSTRACT

Work accomplished during the fourth quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of the nitrogen oxides and sulfur dioxide emissions from Rijke type pulse combustors by using combustion staging and limestone addition. During this quarter an improved coal feed system was installed and the stationary coal bed was replaced with a rotating bed system. This resulted in greatly improved combustor performance by providing a uniform distribution of coal and by preventing agglomeration of ash during combustor operation. The gas analysis system was improved during the report period. A series of baseline tests was conducted to determine the behavior of the Rijke tube combustor under pulsating operation in the absence of measures to reduce  $\text{NO}_x$  or  $\text{SO}_2$ . Tests were conducted with the stationary bed for coal feed rates around 75 g/min for stoichiometric, excess air, and fuel rich conditions. A test with the rotating bed was conducted for stoichiometric conditions. Sound pressure levels, effluent gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$ , and  $\text{SO}_2$ ), and gas temperatures at several levels above the bed were measured for all the tests. The tests with the stationary bed showed little effect of air/fuel ratio on  $\text{NO}_x$  and  $\text{SO}_2$  concentrations for air/fuel ratios between 0.9 and 1.2. Here concentrations of  $\text{NO}_x$  and  $\text{SO}_2$  averaged about 370 ppm and 1200 ppm respectively. The test with the rotating bed demonstrated the superior performance of this bed by increasing the pulsation amplitude by nearly 5 dB and by providing longer running times under more uniform combustion conditions.

## INTRODUCTION

The following report summarizes the work done under DOE Grant No. DE-FG22-88PC88918 during the period October 1, 1989 through December 31, 1989. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

The following work will be described in this report: (1) modification of the coal feed system, (2) replacement of the stationary coal bed with a rotating bed system, (3) improvements in the gas analysis system, (4) tests with the stationary bed, and (5) tests with the rotating bed. The report will conclude with projected work to be accomplished during the next quarter.

## MODIFICATIONS TO RIJKE COMBUSTOR

Based on preliminary tests to be described later in this report, two modifications of the Rijke tube pulse combustor were made in order to improve the performance of the combustor. First the coal feed system was modified to obtain a constant feed rate during combustor operation. Second, the stationary coal bed was replaced by a rotating bed to obtain uniform distribution of coal and to prevent agglomeration of ash and clinkers during combustor operation.

### Coal Feed System

A significant problem became apparent during the preliminary series of experiments conducted in the Rijke tube combustor. The coal feed rate was found to decrease during a test for constant auger speed. The cause appeared to be an accumulation of fine coal particles (dust) at the bottom of the hopper as a result of the auger crushing the coal at the entry point. The fine coal particles were not transported up the nearly vertical auger efficiently since they tended to fall back and they displaced some of the coarser coal particles. Thus they reduced the amount of coal transported up the auger tube. Therefore the present coal feed system was modified to utilize a horizontal auger which eliminated the tendency of coal dust to fall back and accumulate in the bottom of the hopper.

The horizontal auger feed system is shown in Figure 1. In order to use the present system in the horizontal orientation, it was necessary to shorten it to a length of about 65 cm to provide clearance from adjacent apparatus which could not be moved. This required cutting the original auger to a length of 18 cm. The rectangular base of the hopper was welded directly to the auger tube with its long axis parallel to the axis of the auger. Tests conducted with the horizontal auger revealed no significant variation of

coal feed rate during a test or from day to day, thus eliminating the need to calibrate the feed system before every test.

A further modification of the coal feed system was made to facilitate disassembly if necessary. The auger tube was not welded permanently to the coal feed tube. Instead the auger tube was welded to a short flanged section of pipe which was then bolted to the coal feed tube (Figure 1).

An opto-electronic tachometer was installed on the coal feed system in order to obtain instantaneous auger speed (RPM) measurements, replacing the awkward counter/timing method previously used. A slotted disk was attached to the auger shaft such that it passes between a LED light source and a photodiode as shown in Figure 2. As the wheel rotates, it periodically interrupts the light beam giving a pulsed output which is read by a frequency meter. The disk has 60 slots, thus the frequency reading in Hz yields the auger speed directly in RPM.

### Rotating Bed System

A series of preliminary tests conducted with the stationary bed revealed that the performance of the combustor with this bed was unsatisfactory. The coal distribution on the bed was nonuniform and large agglomerates of ash formed during the first few minutes of operation. This allowed most of the air to flow through large gaps in the coal distribution or around the periphery of the bed. When this happened the coupling between the acoustic oscillations and the combustion process was greatly reduced and the pulsations rapidly decayed. Thus pulsating operation of the combustor could be maintained only for a few minutes without taking measures to break up the agglomerates. Since stirring the bed with 3 mm diameter rods inserted through unused thermocouple ports or by suddenly increasing the air flow rate could renew the pulsations, it seemed likely that the same effect could be obtained by using a rotating bed.

The rotating bed assembly is shown in Figure 3. The support for the rotating bed grid is a spoked wheel fabricated from carbon steel which fits closely within a stationary ring of the same material. The ring is attached to the refractory lining of the combustor and provides a seal preventing air from bypassing the bed around its periphery. The bed grid is made of the same stainless steel mesh used previously and it is spot welded to the rotating support wheel. The support wheel is connected by two screws to a 65 cm long 1.2 cm diameter shaft which passes through two ball bearings at the lower end. The bearings are supported by a bearing house flange which is attached to the flanged pipe extending downward from the lower adapter elbow. The rotating bed is driven by a DC geared motor similar to the one used to drive the coal feed auger.

Two tests were conducted during the report period using the rotating bed. These tests demonstrated the superiority of the rotating bed over the stationary bed. The rotating bed successfully eliminated the problems of nonuniform coal distribution and ash agglomeration, and allowed essentially unlimited operation times with large pulsation amplitudes. The bed rotation also broke up the ash into sufficiently small particles that it could fall through the bed grid, thus preventing excessive accumulation of ash on the bed.

#### GAS ANALYSIS SYSTEM

During the first week of the quarter, the new dryer for the gas analysis system arrived and was installed. Also the dessicant in the sample cell in the infrared  $\text{SO}_2$  analyzer was replaced. These measures reduced but did not eliminate the high background  $\text{SO}_2$  readings for ambient air or air from the high pressure supply.

One possible cause for the spurious  $\text{SO}_2$  readings was that the calibration gas presently used, which was certified at 2015 ppm  $\text{SO}_2$  (in nitrogen) several years ago, actually contained much less  $\text{SO}_2$  than this amount. If this was the case, it would make a small background concentration of  $\text{SO}_2$  or an interference effect from residual water vapor seem much larger than it actually was. To investigate this possibility and to improve the calibration process, a new cylinder of calibration gas was obtained with a  $\text{SO}_2$  concentration of about 1000 ppm. After calibrating the analyzer with the new calibration gas, readings were taken using the old calibration gas. These readings were in good agreement with the certified concentration of  $\text{SO}_2$  in the old calibration gas. This eliminated the possibility that the previous calibrations were in error and responsible for the spurious  $\text{SO}_2$  background readings. Using both calibration gases also gives greater confidence in the calibrations.

To investigate further the possibility that residual water vapor is responsible for the high background readings, a dew point hygrometer was installed to measure the water vapor in the sample stream entering the  $\text{SO}_2$  analyzer. These measurements indicated that there were significant amounts of residual water vapor in the sample stream, which partially accounts for the background readings. These background readings, which typically are about 250 ppm, will be subtracted from the data in all experimental runs.

#### BASELINE TESTING

A series of baseline tests were begun during the last month of the quarter. These tests were designed to determine the behavior of the Rijke tube combustor under pulsating operation in the absence of measures to reduce  $\text{NO}_x$  or  $\text{SO}_2$ . Preliminary tests were conducted to determine the optimum coal feed rate for these experiments. Coal feed rates (CFR),

for which there was no significant accumulation of coal on the bed, ranged from 71 g/min to 88 g/min. Tests were then conducted with the stationary coal bed for air/fuel ratios of 1.0, 0.9, and 1.2. Results of these tests indicated the need for a rotating coal bed as discussed above. A test with the rotating bed at an air/fuel ratio = 1.0 was then conducted at the end of the report period.

#### Tests with Stationary Bed

In each of the tests conducted with the stationary bed, measurements of sound pressure level (middle of Rijke Tube), exhaust gas composition ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$ , and  $\text{SO}_2$ ), and gas temperatures at several heights above the bed were made. The results of the first of these tests, for an air/fuel ratio of 1.00 and at a coal feed rate (CFR) of 71 g/min, are presented in Figures 4 through 7.

Figure 4 shows the variation of sound pressure level as a function of time during the test. During the first two minutes of this test the coal was being preheated and ignited by the propane burner located beneath the bed. During this time the combustor was operating in the nonpulsating mode. The propane was then shut off, and the air flow was adjusted for an air/fuel ratio of 1.00. Immediately, pulsating operation began with pressure amplitudes of about 158 dB. With the stationary bed, these sound pressure levels could only be maintained for about four minutes, after which pulsation amplitude decreased to about 154 dB. The pulsations suddenly stopped at  $t = 9.5$  minutes due to the formation of large ash agglomerates and the channeling of air around the periphery of the bed and through gaps in the coal distribution. The pulsations resumed after the agglomerates were broken up by means of rods inserted through unused thermocouple ports at the bed level. This procedure had to be repeated at intervals during the remainder of the test.

The concentrations of carbon dioxide, carbon monoxide, and residual oxygen in the gases leaving the Rijke pulse combustor are shown in Figure 5. The carbon dioxide level, which is an indicator of the completeness of combustion, was fairly constant at about 16.5 percent by volume during most of the test. The prominent dip in  $\text{CO}_2$  concentration was caused by a sudden but temporary increase in air flow rate (air blast) used to break up the ash agglomerates. This graph also shows residual oxygen levels ranging between one and three percent during most of the test. The larger peak in  $\text{O}_2$  concentration was caused by the air blast. The existence of residual oxygen indicates that combustion of the coal was incomplete, either due to unburned coal particles falling through the grid or due to insufficient mixing. The levels of carbon monoxide varied greatly during the test, ranging from as low as 0.1 percent to as high as 1.2 percent by volume (excluding air blast). The  $\text{CO}$  levels

were the highest during periods when the CO<sub>2</sub> levels were the highest and the residual O<sub>2</sub> levels were the lowest.

The emissions of the pollutants, nitrogen oxides and sulfur dioxide, as a function of time during the test are shown in Figure 6. The nitrogen oxides concentrations exhibited much less variation than the sulfur dioxide concentrations during this test. The NO<sub>x</sub> levels ranged from about 350 ppm to nearly 500 ppm. The SO<sub>2</sub> concentrations were much higher, ranging from about 1150 ppm to nearly 1350 ppm. In determining the SO<sub>2</sub> values, a background level of 250 ppm was subtracted from the raw data. Comparison with the data in Figure 4, shows that the SO<sub>2</sub> emissions were highest during the periods of high sound pressure levels. For both pollutants, the minima at about t = 12 minutes corresponds to the air blast used to break up the agglomerates.

Gas temperatures at three heights above the bed (H.A.B.) are shown in Figure 7 for the test with an air/fuel ratio of 1.00 and with the stationary bed. At each height the temperature was measured using a Type K thermocouple located at the axis of the combustor. As expected the temperature decreases with increasing height above the bed due to heat losses through the walls. The gradual increase in temperature with time indicates that the refractory lined walls had not reached the steady state temperature, that is, they were still heating up during the test.

Tests were also conducted using the stationary bed for pulsating operation with excess air (air/fuel ratio = 1.2) and for fuel rich operation (air/fuel ratio = 0.9). The results of these tests are summarized in Table 1 below, where the test with an air/fuel ratio of 1.0 is included for comparison.

Table 1. Results of Tests With Stationary Bed.

Air/ Fuel Ratio	CFR g/min	SPL dB	Freq. Hz	CO <sub>2</sub> %	CO %	O <sub>2</sub> %	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
0.9	88	156.9	69	16.0	0.58	2.4	390	1160
1.0	71	155.4	69	16.7	0.58	1.4	370	1250
1.2	73	155.9	71	14.7	0.34	3.8	350	1100

These results show that the air/fuel ratio has only a small effect on the emissions of NO<sub>x</sub> and SO<sub>2</sub> for the small range of air/fuel ratios covered in these tests. In each of these tests there was significant amounts of residual oxygen in the exhaust gases, which indicates that combustion was incomplete for the stoichiometric and fuel rich cases. The smaller CO<sub>2</sub> concentration for the case with excess air was due mainly to the dilution effect of the additional air.

## Tests with Rotating Bed

A single test with the new rotating bed was conducted near the end of the report period. For this test the air/fuel ratio was 1.00 and the coal feed rate was 75 g/min. The results of this test are presented in Figures 8 through 10.

The sound pressure levels for the test with the rotating bed are shown in Figure 8. Here it is seen that the pulsation amplitudes were nearly constant during the entire test; the variation in amplitude was less than 0.7 dB above or below the mean amplitude of 159.8 dB. During this test the agglomerates were continuously broken up by the action of the rotating bed, and the distribution of coal on the bed was very uniform. Furthermore the ash particles were ground down to small enough sizes so that they continuously fell through the bed grid, thus preventing accumulation of coal and ash on the bed. This accounts for the superior performance of the rotating bed over the stationary bed in maintaining large amplitude pulsations.

The concentrations of carbon dioxide, oxygen, and carbon monoxide in the exhaust gases are shown in Figure 9 for the test with the rotating bed. After an initial transient period of about five minutes, the concentrations of these gases attained nearly constant values for the remainder of the test. The concentration of carbon dioxide reached a steady value of 16.2 percent by volume, while the concentration of residual oxygen was reduced essentially to zero. This indicates complete combustion of the coal during pulsating operation. The concentration of carbon monoxide averaged about 1.4 percent during the middle of the test, and it decreased significantly during later stages of the test. The high levels of CO indicate that a small amount of excess air will be needed for good combustion efficiency of this system.

The emissions of nitrogen oxides and sulfur dioxide for this test are presented in Figure 10. Both  $\text{NO}_x$  and  $\text{SO}_2$  concentrations exhibited sharp peaks during the transient period, but soon reached steady state values. The  $\text{NO}_x$  concentration averaged about 360 ppm during the early phases of the test and gradually increased to about 425 ppm toward the end of the test. The  $\text{SO}_2$  concentration fluctuated about a mean of about 1300 ppm during the test. Both  $\text{NO}_x$  and  $\text{SO}_2$  concentrations measured with the rotating bed were similar to the values obtained with the stationary bed for an air/fuel ratio of 1.00.

## FUTURE WORK

During the next quarter the baseline testing with the rotating bed system will be completed. These tests will be conducted at a coal feed rate of 75 g/min and will cover the

range of air/fuel ratios from 0.6 to 1.5. Two or three 15-minute runs will be conducted for each value of air/fuel ratio. This series of tests will be followed by a period of data evaluation and analysis.

After the baseline tests are completed, a series of tests will be conducted to determine the effect of air staging on  $\text{NO}_x$  emissions during pulsating combustion. Air will be injected at several different heights above the coal bed, while the coal is being burned under fuel rich conditions. In each experimental run, the total air/fuel ratio will be held constant while the primary air/fuel ratio will be varied. Air staging tests will be run with an air/fuel ratio of 1.00 (stoichiometric) and at excess air conditions. Tests will also be conducted with air staging under nonpulsating conditions in order to determine the effect of pulsations on the ability of air staging to reduce  $\text{NO}_x$  emissions.

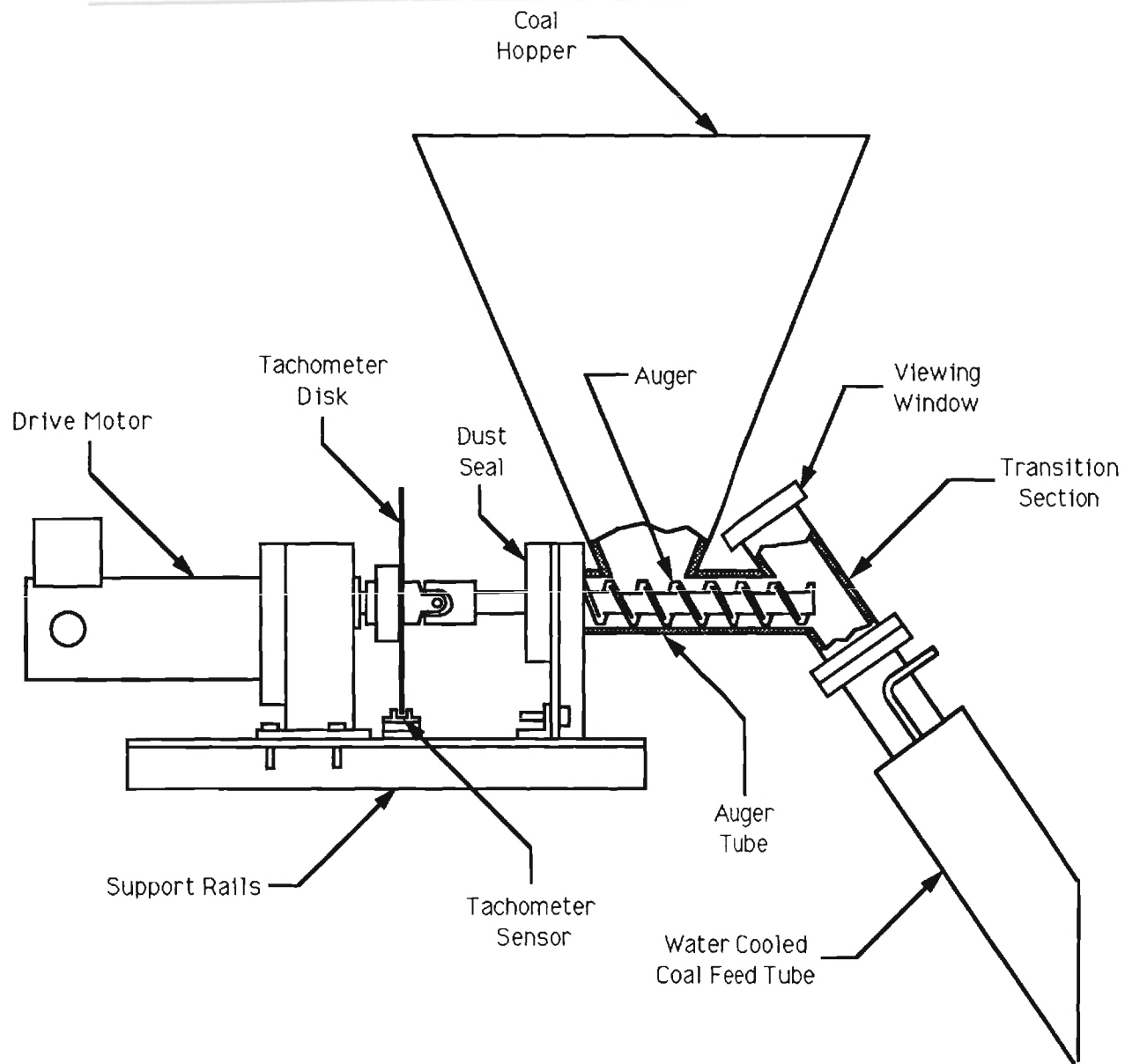


Figure 1. Horizontal Coal Feed Auger.

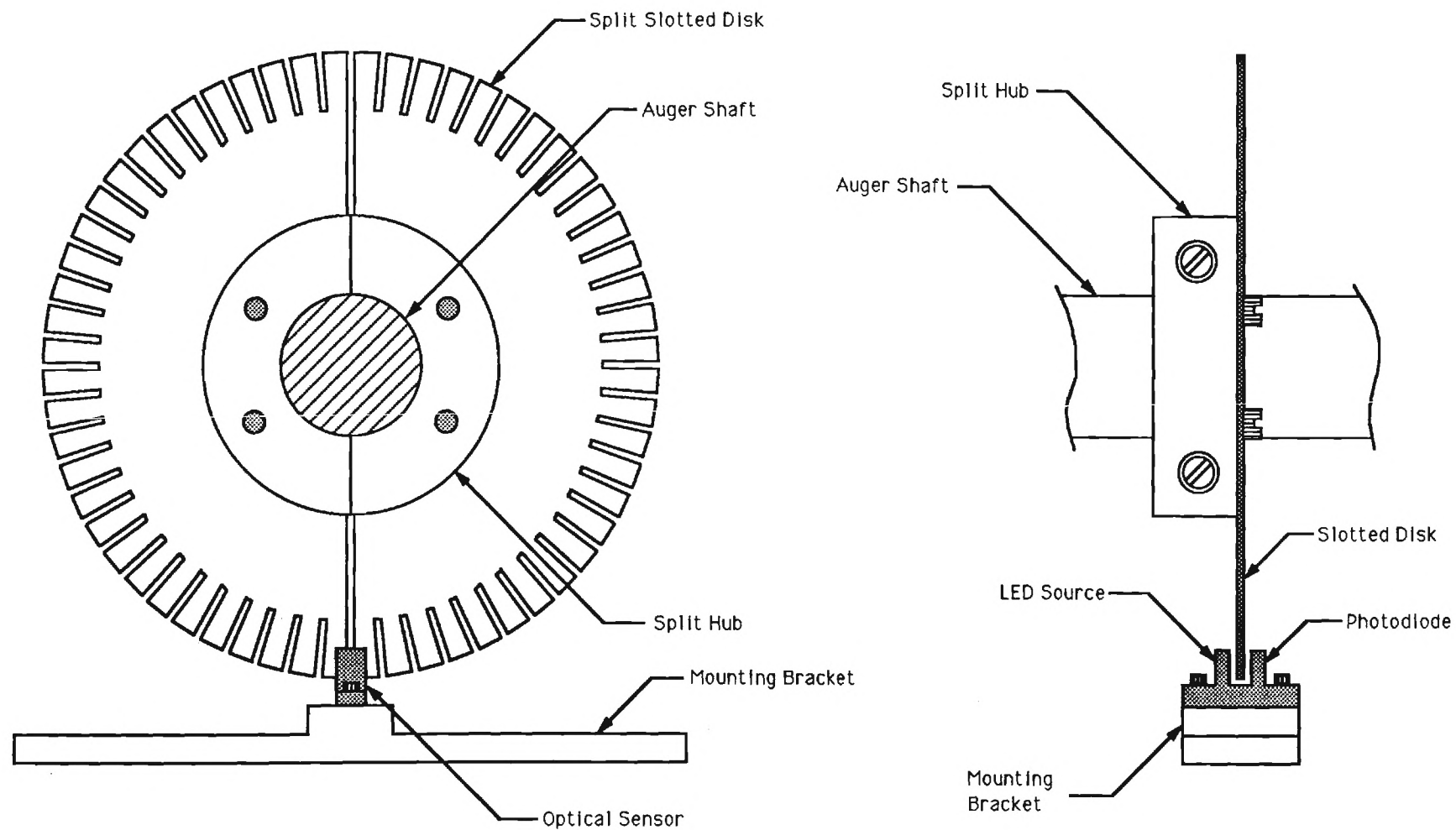


Figure 2. Opto-electronic Tachometer for Coal Feed Auger.

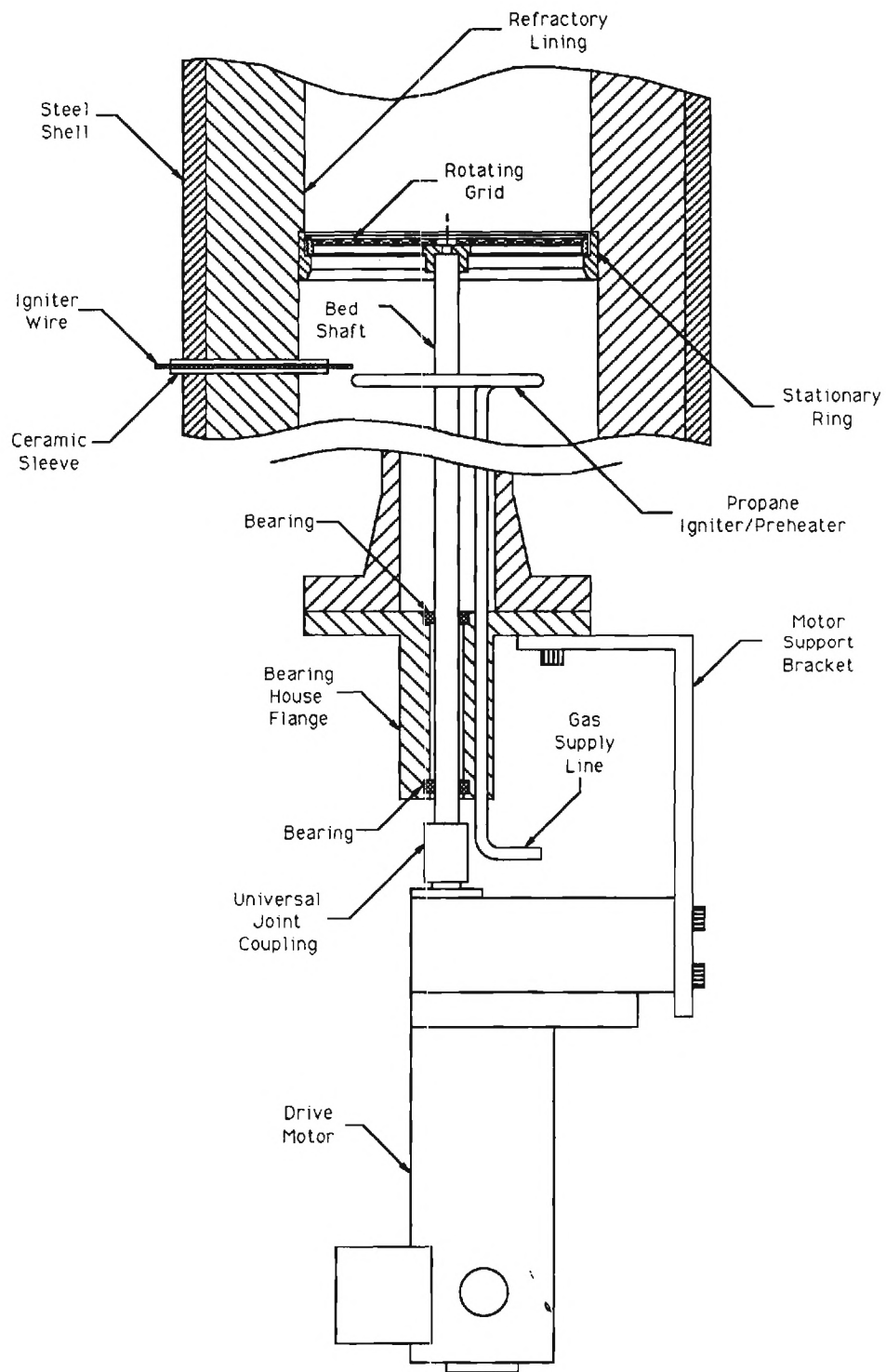


Figure 3. Rotating Bed Assembly.

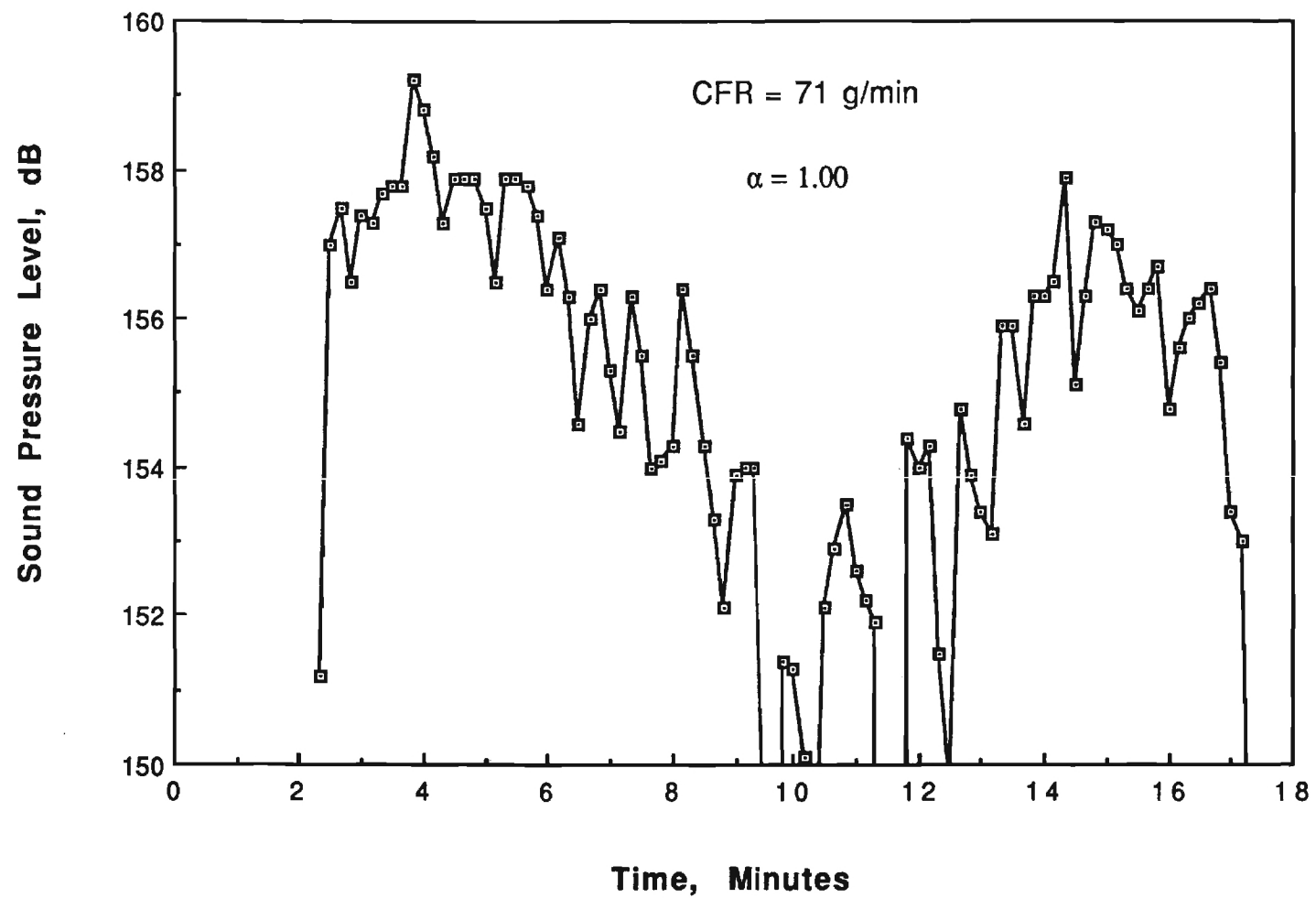


Figure 4. Sound Pressure Levels for Test with Stationary Bed.

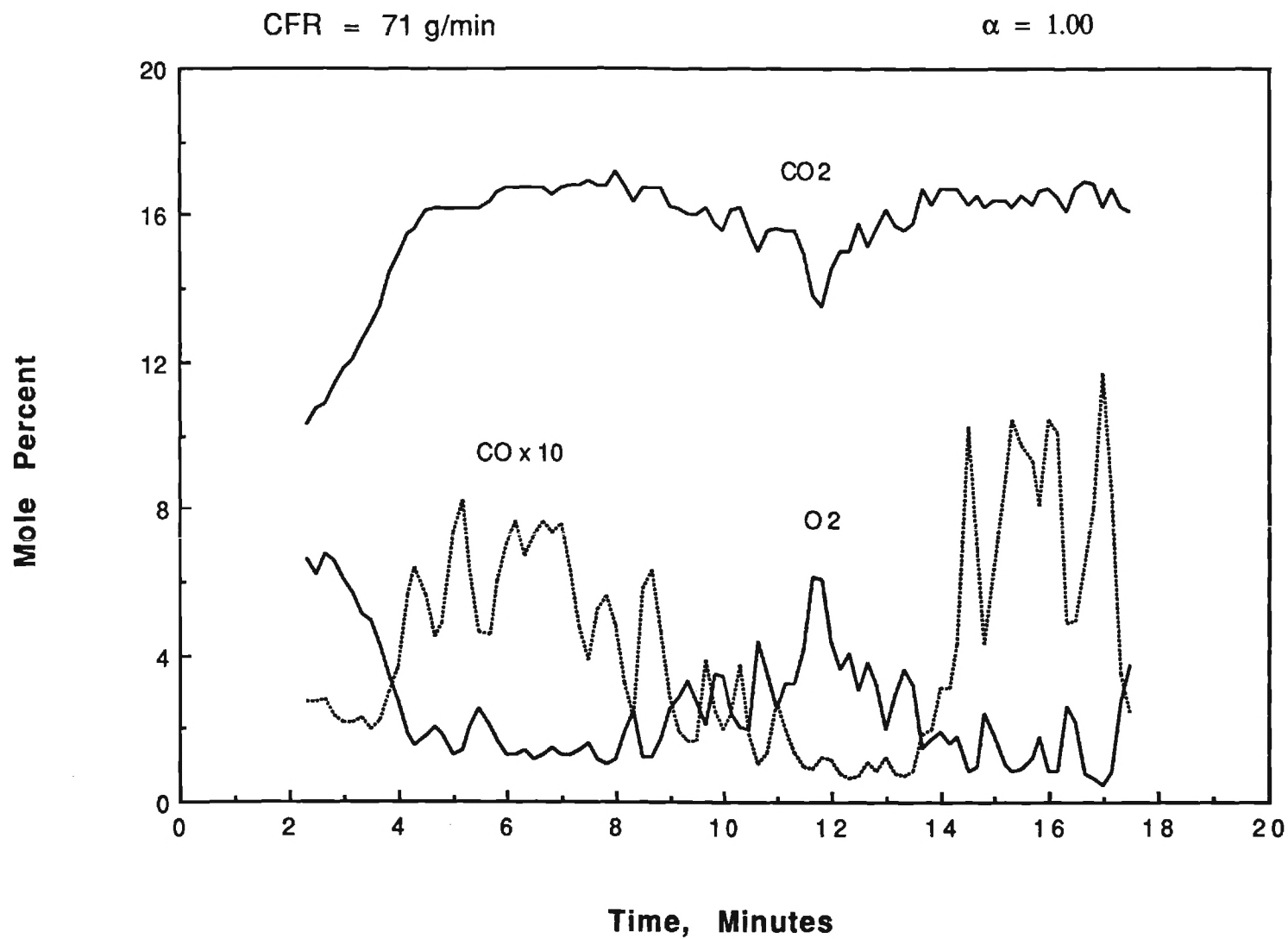


Figure 5. Exhaust Gas Carbon Dioxide, Oxygen, and Carbon Monoxide Concentrations for Stationary Bed.

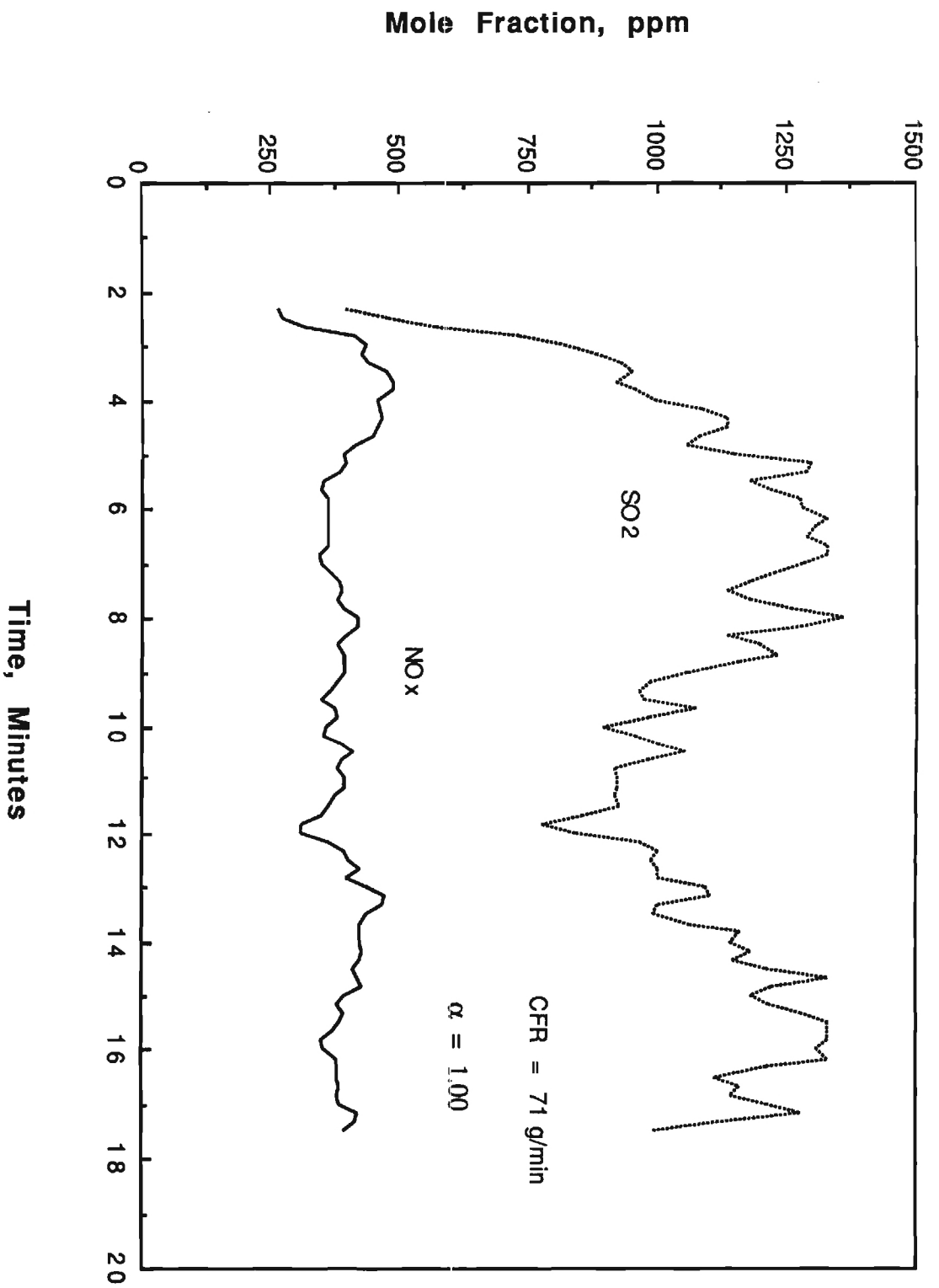


Figure 6. Nitrogen Oxides and Sulfur Dioxide Emissions for Test with Stationary Bed.

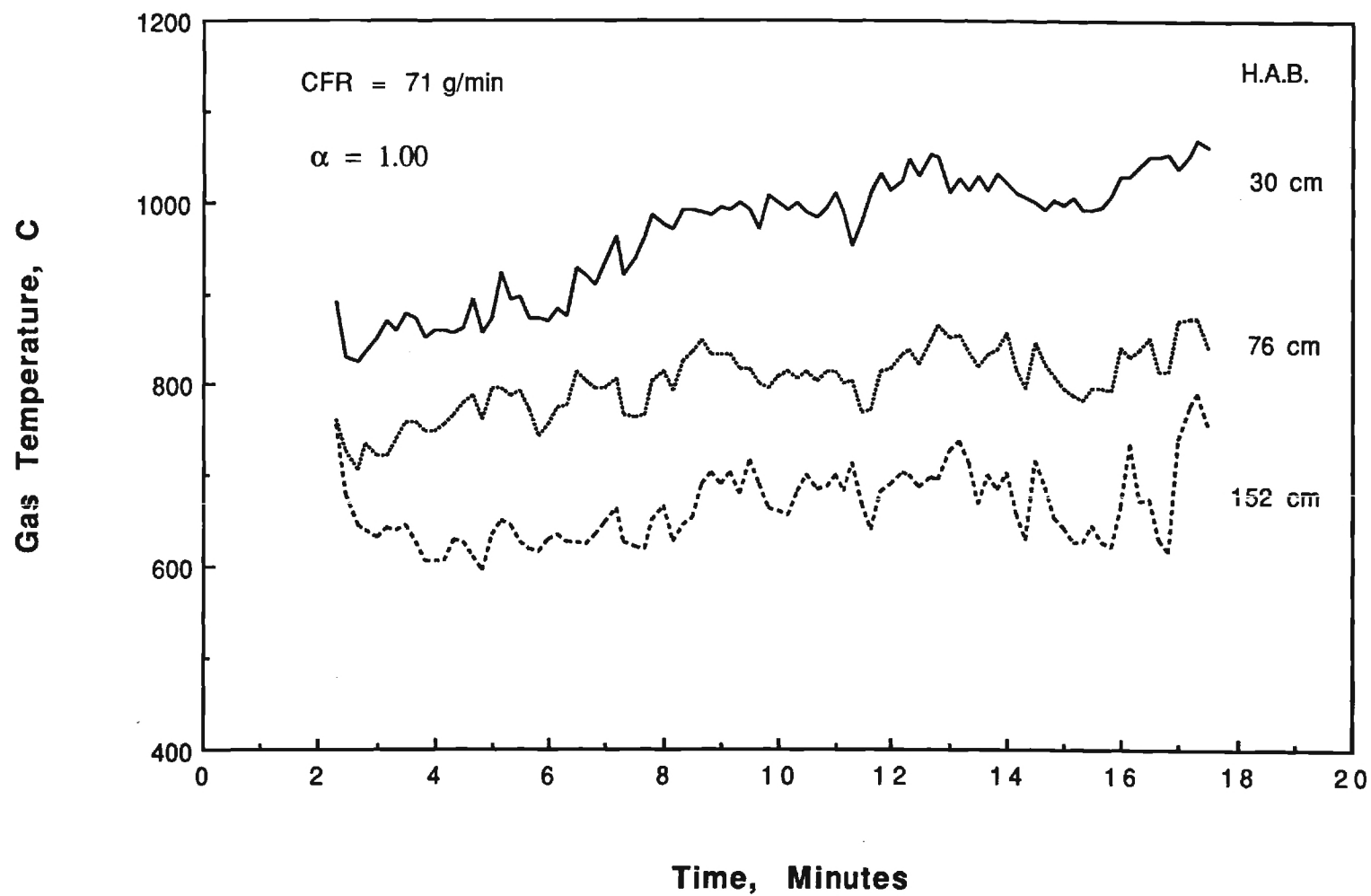


Figure 7. Gas Temperatures for Test with Stationary Bed.

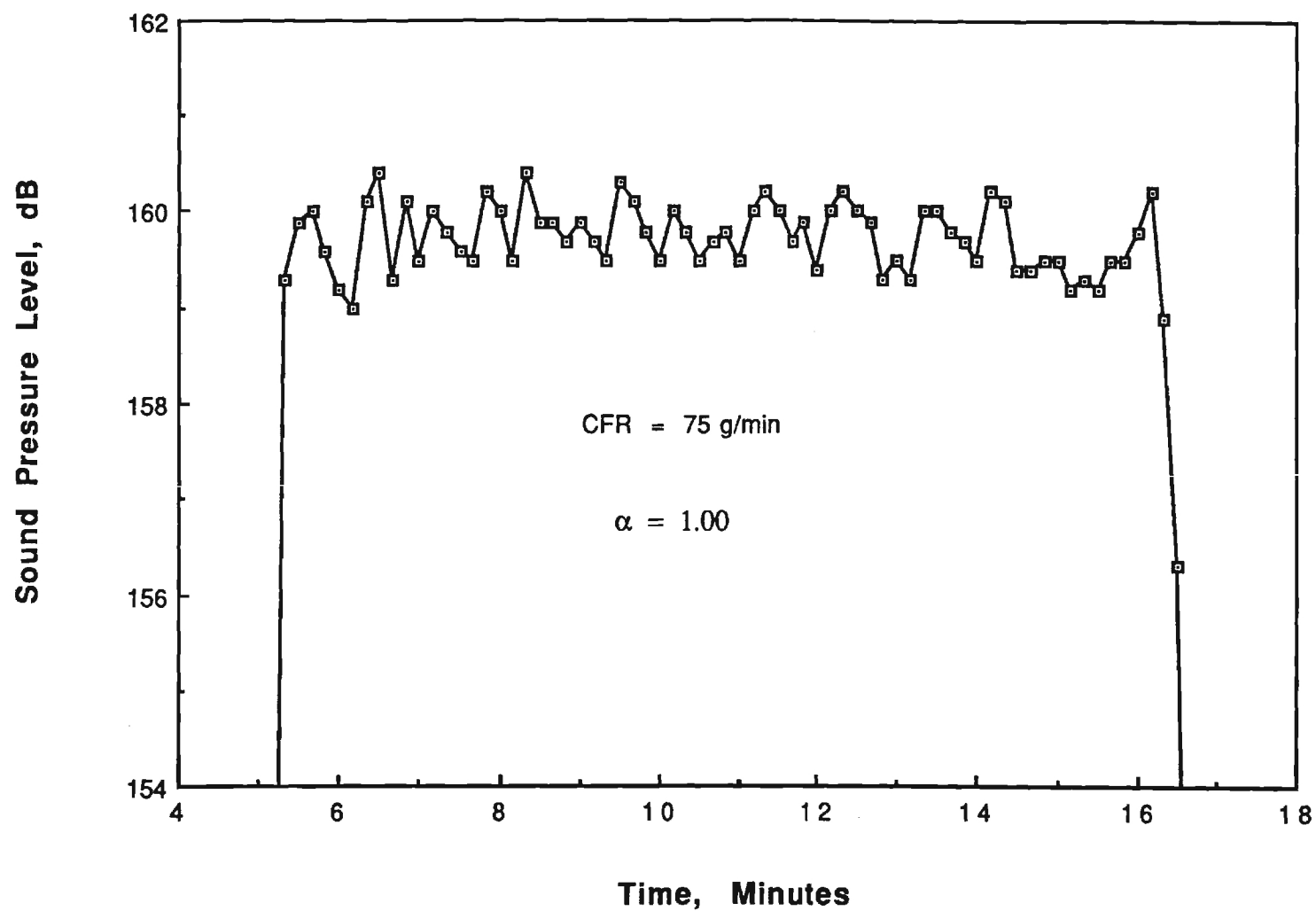


Figure 8. Sound Pressure Levels for Test with Rotating Bed.

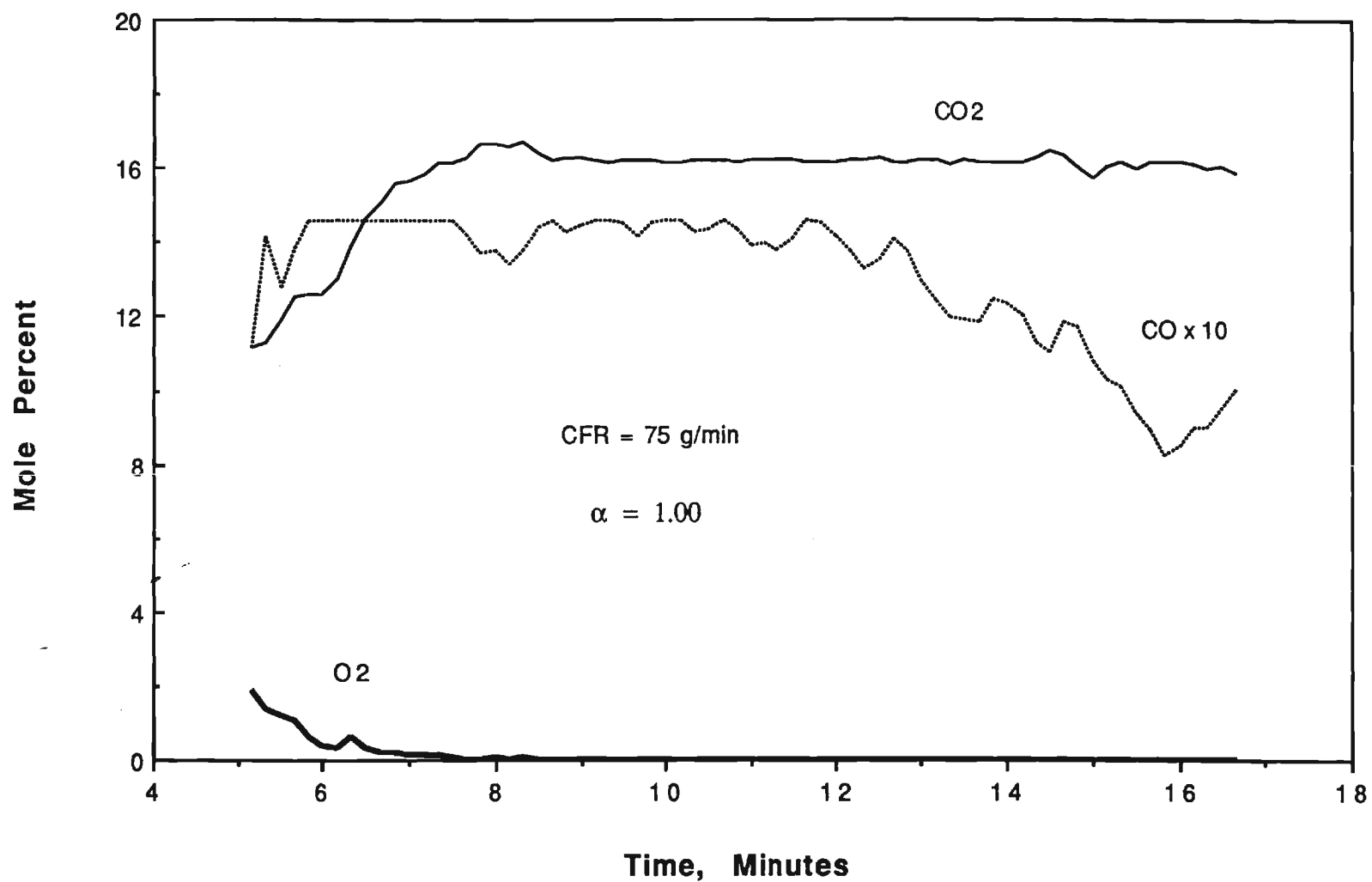


Figure 9. Exhaust Gas Carbon Dioxide, Oxygen, and Carbon Monoxide Concentrations for Rotating Bed.

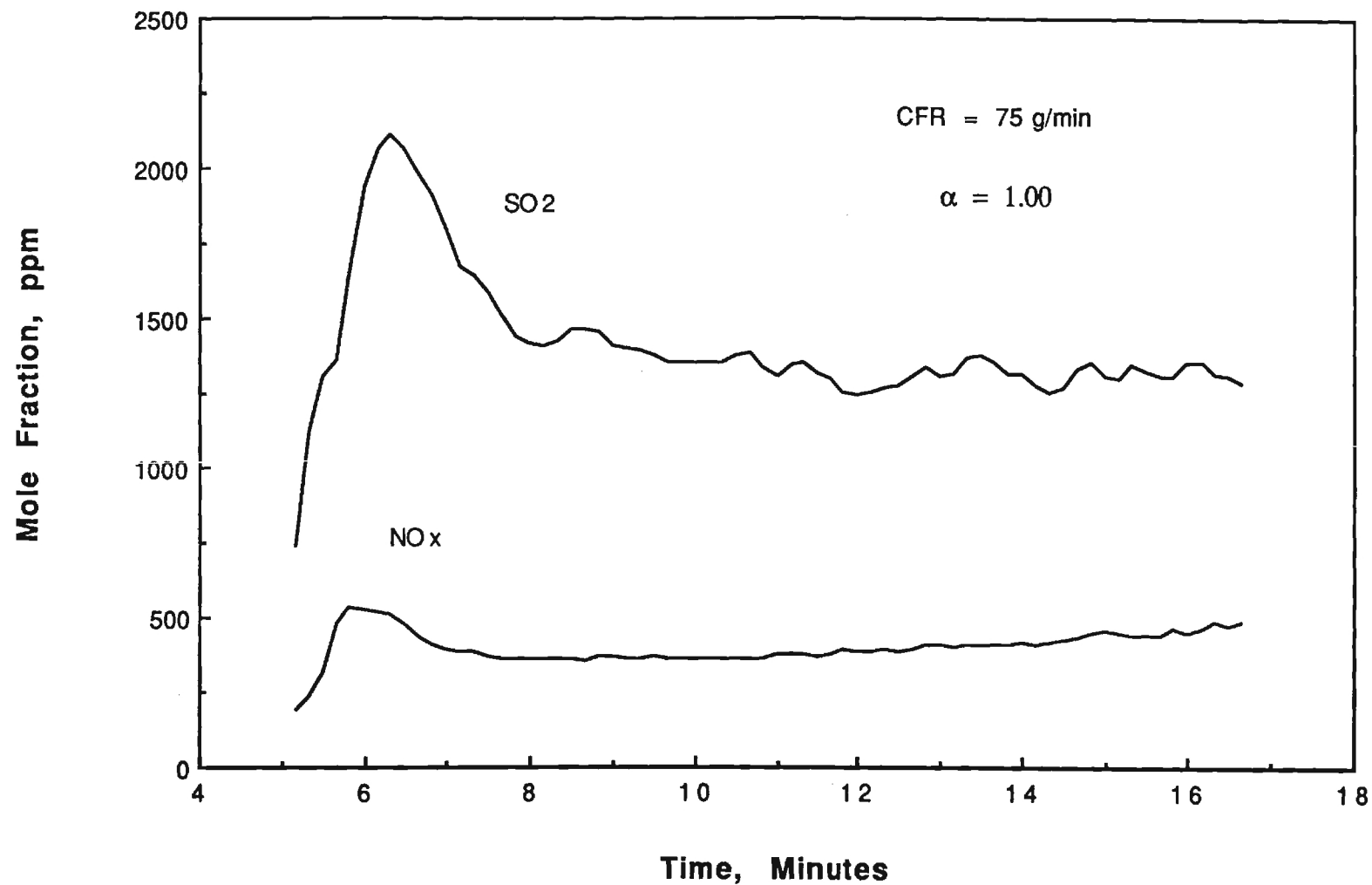


Figure 10. Nitrogen Oxides and Sulfur Dioxide Emissions for Test with Rotating Bed.

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## **COAL PULSE COMBUSTION RESEARCH**

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January 1, 1990 - March 31, 1990

Prepared by

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May 1990

Technical Project Officer - Perry Bergman

Prepared for

United States Department of Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

## ABSTRACT

Work accomplished during the sixth quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

During this quarter the assembly and installation of the sorbent feed system was completed.

A series of baseline experiments was then completed to determine the  $\text{NO}_x$  and  $\text{SO}_2$  emissions in the absence of sorbent addition or combustion staging. For the baseline tests, sound pressure levels, frequencies, exhaust gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and temperatures were measured as a function of air/fuel ratio for a fixed coal feed rate of 75 g/min. Sound pressure level was a maximum, about 160 dB, for stoichiometric conditions. Nitrogen oxides production was between 400 and 600 ppm for the entire range of air/fuel ratios investigated. The maximum concentration of  $\text{NO}_x$  (about 590 ppm) was obtained for air/fuel ratios of 1.2 and 1.3, while minimum  $\text{NO}_x$  (about 400 ppm) occurred at an air/fuel ratio of 0.8. Sulfur dioxide concentrations were near 1450 ppm for air/fuel ratios below 1.1, and they decreased steadily for larger air/fuel ratios primarily due to the dilution effect of the excess air.

Next a series of air staging tests was conducted to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the  $\text{NO}_x$  emissions. For the air staging tests, values of each of the measured quantities were obtained as a function of the primary air/fuel ratio, with the total air/fuel ratio always stoichiometric. Data was obtained from three secondary injection heights above the bed: 20 cm, 27 cm and 37 cm. Sound pressure level ranged between 154 dB at a primary air/fuel ratio of 0.5 to about 160 dB for the case without air staging, and it was little affected by injection height. Residual oxygen levels measured during these experiments indicated that combustion of the coal gases by the secondary air injection was not complete, even though the total air/fuel ratio was stoichiometric. Nitrogen oxides ranged between 400 ppm and 600 ppm with no clear effect of air staging.

Finally a series of non-pulsating tests was performed to determine the effect of pulsations on the  $\text{NO}_x$  emissions. Results of the non-pulsating tests showed much lower combustion efficiency under non-pulsating conditions. Carbon dioxide mole fractions were about 6 percent while residual oxygen was about 14 percent, indicating incomplete combustion of the coal. The non-pulsating experiments showed a significant decrease in  $\text{NO}_x$  production with decreasing air/fuel ratio. For stoichiometric conditions  $\text{NO}_x$  concentrations were about 180 ppm, which decreased to about 115 ppm at an air/fuel ratio of about 0.5. The  $\text{NO}_x$  concentrations under non-pulsating combustion were less than half (stoichiometric) to a fourth (air/fuel ratio of 0.5) of those produced under pulsating conditions. Comparison of the results of the pulsating and non-pulsating tests indicate that pulsations greatly increase the combustion efficiency for a given air/fuel ratio. Unfortunately pulsations also greatly increase the efficiency with which the fuel-bound nitrogen is converted into nitrogen oxides.

## INTRODUCTION

The following report summarizes work done under DOE Grant No. DE-FG-88PC88918 during the period January 1, 1990 through March 31, 1990. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

The following work will be described in this report: (1) assembly and installation of the sorbent feed system, (2) baseline tests to determine the  $\text{NO}_x$  and  $\text{SO}_2$  emissions in the absence of sorbent addition or combustion staging, (3) air staging tests to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the  $\text{NO}_x$  emissions, and (4) non-pulsating tests to determine the effect of pulsations on the  $\text{NO}_x$  emissions. The report will conclude with projected work to be accomplished during the next quarter.

## SORBENT FEED SYSTEM

The assembly and installation of the sorbent feed system was completed during the quarter. The sorbent feed assembly consists of a drive motor, hopper and auger mounted on support rails as shown in Figure 1. The hopper and auger have been described in Reference 1. The support rail consists of two angle-section steel beams 36 cm long placed side by side to form a single U-channel beam 5 cm wide. The motor is bolted to short angle-section beams which are welded to the support rail. The hopper is supported at its base by a 5 cm wide piece of 3 mm thick steel plate which was cut to match the hopper base and bolted to the existing holes on the hopper base. The bottom of this bracket is welded to a 5 cm long piece of angle-section beam which is bolted to the support rail. Finally, the top end of the hopper is supported by two 1.6 cm diameter aluminum rods 6.4 cm long which are bolted to the back of the hopper and to the support rail.

A tachometer system was installed on the sorbent feed auger shaft to determine the instantaneous rotational speed of the auger which is needed in order to accurately measure the sorbent feed rate into the combustor. This tachometer is similar to the one installed on the coal feed system, except that the slotted tachometer disk is smaller (10 cm diameter) and is not split into two halves. Like the slotted disk for the coal feed system, the sorbent feed disk has 60 slots. The slotted disk is bolted to a hub which fits over the auger shaft and is secured by a setscrew. A bracket mounted on the support rails holds an opto-electronic sensor whose signal is sent to the same electronic pulse counter used for the coal feed system.

The sorbent feed system was then installed on the Rijke pulse combustor. The sorbent feed assembly (motor, hopper and auger) was mounted vertically above the sorbent injection point as shown in Figure 2. The upper end of the auger was attached to the venturi section where the pulverized limestone or dolomite is entrained by a low pressure high velocity air stream. The air is supplied by the same secondary air supply used for air staging experiments. The entrained sorbent particles are then carried downward to the injector head (see Ref. 1) and enter the combustor just above the coal bed.

## BASELINE TESTING

A series of baseline tests was conducted to determine the performance of the combustor without combustion staging or sorbent addition. For these tests the coal feed rate was 75 g/min and air/fuel ratios ranged from 0.6 to 1.5. These tests were conducted according to the following procedure. Beginning with an empty bed, the combustor was preheated with propane for about five minutes under non-pulsating conditions. During the preheat phase, the propane flow rate was about 25 standard liter/min (SLM) and the air flow rate was about 1020 SLM. Next the bed rotation and coal feed were started with the propane still on. After about two minutes, the coal

was burning under non-pulsating conditions, and the primary air flow was adjusted for the desired air/fuel ratio and the propane was shut off. Immediately, pulsating operation began with pressure amplitudes of about 160 dB. Pulsating operation was usually maintained for periods ranging from 15 to 25 minutes, but longer operating times were possible.

The coal used in all of the tests was a bituminous coal obtained from Georgia Power Company's Plant McDonough located near Atlanta. The coal was sieved to give a range of particle sizes between 6 mm and 12 mm in diameter. The ultimate analysis of the coal was 72.2% carbon, 5.09% hydrogen, 1.48% nitrogen, 1.26% sulfur and 6.60% oxygen. The proximate analysis of the coal as received was 5.60% moisture, 31.98% volatiles, 10.68% ash and 51.74% fixed carbon. The heating value of the coal as received was 29,060 kJ/kg.

For each of the baseline tests, sound pressure levels, frequencies, exhaust gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and temperatures were measured as a function of air/fuel ratio ( $\alpha$ ) for a fixed coal feed rate of 75 g/min. A total of 22 baseline tests were conducted with at least two tests for each value of  $\alpha$ . Since the measured quantities fluctuated with time during the 15-20 minute tests, data was time averaged over two or three time periods (each lasting 3-5 minutes) for each test. Plots of the measured quantities as a function of time were used to determine which one of the time averages was more typical of the test. This procedure determined a representative value for each of the measured quantities for each test. For each air/fuel ratio, the time averaged data from the appropriate tests were then averaged and tabulated. The results of the tests are shown in Table I. Plots were generated of each quantity as a function of  $\alpha$ ; these are given in Figures 3 through 5.

Sound pressure level and frequency as a function of  $\alpha$  are shown in Figure 3. Sound pressure level was a maximum, about 160 dB, for stoichiometric conditions ( $\alpha = 1.00$ ). The lowest amplitude recorded was 156 dB at air/fuel ratios of 0.6 and 0.7. The pulsation

frequency increased as the air/fuel ratio was increased, ranging from about 64 Hz at  $\alpha = 0.6$  to about 73 Hz at  $\alpha = 1.5$ . These frequencies are consistent with the fundamental longitudinal acoustic mode of the open-ended Rijke tube combustor. The changes in frequency with air/fuel ratio are due to changes in the temperature distribution and composition of the gases in the region between the coal bed and the exhaust outlet.

Table I. Averaged Sound Pressure Levels, Frequencies and Exhaust Compositions for Baseline Tests.

No. of Tests	$\alpha$	SPL (dB)	Freq (Hz)	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)
2	0.6	155.9	64.5	15.4	1.12	484	NA	0.29
5	0.7	155.6	66.5	14.5	0.73	451	1420	1.36
2	0.8	159.0	65.0	16.2	1.01	398	1450	0.04
4	1.0	159.8	66.0	16.6	0.83	443	1420	0.65
2	1.1	158.3	70.0	16.5	0.42	502	1480	0.52
2	1.2	158.0	71.5	15.1	0.05	585	1270	3.16
2	1.3	157.7	72.0	10.5	0.02	592	1140	5.83
2	1.5	157.9	73.0	11.3	0.06	559	940	6.47

Carbon dioxide, carbon monoxide and residual oxygen concentrations are shown in Figure 4. Carbon dioxide levels were maximum (16.5 percent) for stoichiometric conditions, and they were above 16 percent for air/fuel ratios between 0.8 and 1.1. Carbon monoxide concentrations ranged between 0.7 and 1.2 percent for stoichiometric and fuel rich combustion, but CO levels dropped sharply when excess air was added, becoming less than 0.06 percent for  $\alpha = 1.2$  or greater. For air/fuel ratios below 1.1, residual oxygen concentrations were small (less than one percent), but they increased sharply as excess air was increased, reaching 6 to 6.5 percent for air/fuel ratios of 1.3 and above.

Nitrogen oxides and sulfur dioxide concentrations are shown in Figure 5. The upper graph in Figure 5 shows that nitrogen oxides production was between 400 and 600 ppm for the entire range of air/fuel ratios investigated. The maximum concentration of  $\text{NO}_x$  (about 590 ppm) was obtained for air/fuel ratios of 1.2 and 1.3, while minimum  $\text{NO}_x$  (about 400 ppm) occurred at  $\alpha = 0.8$ . This graph also shows that sulfur dioxide concentrations were near 1450 ppm for air/fuel ratios below 1.1, and they decreased steadily for larger air/fuel ratios primarily due to the dilution effect of the excess air. To remove this dilution effect and allow comparison with other data, the measured  $\text{NO}_x$  and  $\text{SO}_2$  concentrations were reduced to a 15% excess air (3% excess oxygen) basis. The reduced  $\text{NO}_x$  and  $\text{SO}_2$  concentrations are shown in the lower graph of Figure 5. This reveals a much more pronounced effect of air/fuel ratio on the  $\text{NO}_x$  emissions from the pulse combustor. The reduced  $\text{NO}_x$  concentrations were about 250 ppm for  $\alpha$  below 0.8, they increased rapidly as  $\alpha$  increased from 0.8 to 1.3, and they reached about 725 ppm for  $\alpha = 1.5$ . The reduced  $\text{SO}_2$  concentrations exhibited a strong increase with increasing air/fuel ratio for  $\alpha$  less than 1.1, ranging from about 850 ppm to 1400 ppm. For higher air/fuel ratios, there was a gradual decrease in the reduced  $\text{SO}_2$  concentration.

### AIR STAGING TESTS

A series of air-staging tests was completed in which secondary air was injected at various heights above the bed (20 cm to 37 cm). The secondary air supply system and injector is shown in Figure 2. In each test the total air/fuel ratio ( $\alpha_t$ ) was stoichiometric, that is,  $\alpha_t = 1.00$ . Each of these tests were divided into three segments lasting about five minutes each. In the first test segment, a primary air/fuel ratio of 1.0 was used (no secondary air injection). The primary air/fuel ratio was then reduced to 0.7 in the second test segment and to 0.5 in the third test segment. Time averaged values of sound pressure levels, frequencies, exhaust gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and temperatures were obtained for each test segment.

A total of 10 air staging tests were conducted. In the first test the secondary air was injected at a height of 53 cm above the coal bed. Results of this test indicated that the secondary air should be injected closer to the bed. For the remaining tests, two tests were conducted with secondary air injection at 37 cm above the bed, three tests were run with air staging at 27 cm above the bed, and four tests were conducted with air staging at 20 cm above the bed. For each secondary air injection height and each primary air/fuel ratio,  $\alpha_1$ , the time averages of each of the measured quantities for the appropriate tests were averaged. The resulting values were then tabulated and plotted as a function of the primary air/fuel ratio,  $\alpha_1$ , for three secondary injection heights above the bed: 20 cm, 27 cm and 37 cm. These data are presented in Table II and Figures 6 through 10.

Table II. Averaged Sound Pressure Levels and Exhaust Gas Compositions for Air Staging Tests.

Air Staging Location (cm)	$\alpha_1$	SPL (dB)	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)
20	0.4	151.3	12.7	0.05	597	1190	5.7
	0.5	154.1	14.5	0.20	555	1230	4.1
	0.7	156.3	15.8	0.15	535	1260	2.8
	1.0	159.9	14.1	0.58	505	1470	2.3
27	0.5	153.6	13.6	0.05	453	1170	4.5
	0.67	156.2	15.5	0.05	498	1300	3.1
	0.7	156.6	15.5	0.10	516	1210	2.7
	1.0	159.7	15.7	0.45	485	1310	1.8
37	0.5	153.8	12.7	0.10	429	1090	5.2
	0.7	155.7	15.0	0.15	454	1250	3.0
	1.0	159.2	15.3	0.35	471	1310	2.1
53	0.67	157.5	8.1	0.70	330	1320	11.5

Figure 6 shows that sound pressure levels increased nearly linearly from 154 dB at  $\alpha_1 = 0.5$  to about 160 dB at  $\alpha_1 = 1.0$ . Secondary air injection height had very little affect on the amplitude and frequency of the pulsations.

Carbon dioxide concentrations for the air staging tests are shown in Figure 7. Except for the lowest secondary air injection point (20 cm), the  $\text{CO}_2$  concentration increased monotonically with increasing primary air/fuel ratio. Carbon dioxide concentrations ranged between 12.5 percent and nearly 16 percent, with the lower values corresponding to  $\alpha_1 = 0.5$ . Except for the unexpected decrease in  $\text{CO}_2$  concentration for secondary air injection at 20 cm,  $\text{CO}_2$  concentrations increased only slightly between  $\alpha_1 = 0.7$  and  $\alpha_1 = 1.0$ . The concentration of  $\text{CO}_2$  also decreased significantly with increasing height of the secondary air injection point. Carbon dioxide concentrations measured in the air staging tests at  $\alpha_1 = 1.0$  were somewhat lower than those measured in the baseline tests at stoichiometric combustion conditions. This was probably due to the dilution effect of a small amount of secondary air used to cool the injection head for the case of  $\alpha_1 = 1.0$ .

The measured carbon monoxide emissions for the air staging tests are shown in Figure 8. Carbon monoxide concentration generally increased with increasing primary air/fuel ratio. Carbon monoxide concentration varied between about 0.05 and 0.6 percent, with the higher values for  $\alpha_1 = 1.0$  (no secondary air injection). Increasing the secondary air injection height generally reduced the amount of CO in the exhaust gases. The CO concentrations measured in the air staging tests for  $\alpha_1 = 1.0$  were generally lower than those measured in the baseline tests under stoichiometric combustion conditions.

Measured oxygen concentrations in the exhaust gases during the air staging tests are shown in Figure 9. Residual oxygen levels were higher for lower values of the primary air/fuel ratio, with a maximum of 5.7 percent for  $\alpha_1 = 0.4$  with secondary air injection at

20 cm above the primary combustion zone. For  $\alpha_1 = 1.0$ , residual oxygen was about 2 percent. Residual oxygen levels increased as the secondary air injection height was increased. These residual oxygen levels indicate that combustion of the coal gases by the secondary air injection was not complete, since the total air/fuel ratio was stoichiometric. Residual oxygen concentrations in the air staging tests for  $\alpha_1 = 1.0$  were somewhat higher than those measured in the baseline tests under stoichiometric combustion conditions.

The measured nitrogen oxides concentrations in the exhaust gases for the air staging tests are shown in Figure 10. Nitrogen oxides emissions ranged between 400 ppm and 600 ppm with only moderate reductions due to air staging. For secondary air injection at 20 cm above the bed, decreasing  $\alpha_1$  increased the  $\text{NO}_x$  concentrations, but reducing  $\alpha_1$  yielded slight decreases in the  $\text{NO}_x$  emissions for the higher injection points. Increasing the height of the secondary air injection point resulted in decreased  $\text{NO}_x$  emissions, especially for the smaller primary air/fuel ratios.

Although the object of the air staging experiments was the reduction of  $\text{NO}_x$  emissions, the effect of air staging on sulfur dioxide emissions was also obtained. These results are shown in Figure 11. At the lowest secondary air injection point, sulfur dioxide emissions ranged from about 1200 ppm for  $\alpha_1 = 0.4$  to nearly 1500 ppm for  $\alpha_1 = 1.0$ . Raising the secondary injection point clearly decreased  $\text{SO}_2$  emissions for  $\alpha_1 = 0.5$  but had little effect on  $\text{SO}_2$  concentrations for  $\alpha_1 = 0.7$ .

The effect of air staging on the temperature distributions in the combustor downstream of the coal bed are shown in Figure 12. Here, temperature profiles are shown for secondary air injection at 37 cm above the bed for different primary air/fuel ratios. The curve for  $\alpha_1 = 1.0$  represents stoichiometric burning without air staging, where the monotonic decrease in temperature with increasing height above the coal bed is due to heat losses through the combustor walls. For the two cases with secondary air injection, the heat release in the

secondary combustion zone results in higher temperatures in this region (25 - 45 cm above the bed) than those obtained without air staging. For positions higher than 75 cm above the bed, the temperatures obtained with air staging are considerably lower than those obtained without secondary air. Since the total air/fuel ratio for all three cases is the same, this temperature deficit at the combustor exit is a further indication of the incomplete combustion and resultant smaller heat release obtained with air staging under pulsating combustion conditions.

The results of the combustion staging tests indicated that air staging was ineffective at significantly reducing the nitrogen oxides emissions. The reason for this is that lowering the primary air/fuel ratio for pulsating operation resulted in only moderate reductions in the nitrogen oxides emissions. Also it was found that incomplete combustion in the secondary combustion zone resulted in poor overall combustion efficiency.

## NON-PULSATING TESTS

A series of experiments were conducted under non-pulsating combustion conditions in order to determine the effect of pulsations on the performance of the combustor, particularly regarding  $\text{NO}_x$  and  $\text{SO}_2$  emissions. Non-pulsating operation was obtained by partially opening the viewing window at the middle of the combustor, which forced the pressure perturbation to be zero where the pressure oscillations for the fundamental acoustic mode normally have their maximum amplitude. To reduce the air leakage through this large opening, it was covered by a piece of cloth. A total of five non-pulsating tests were conducted. Each test was divided into four or five test segments of about five minutes length. Most of the tests were conducted without air staging, but in one of the tests secondary air was injected 20 cm above the bed.

The results of the non-pulsating tests without air staging are shown in Table III and in Figures 13 through 16. The data shown are time-averaged values for the appropriate test segments. In Table III,  $T_1$  is the gas temperature measured on the axis of the combustor 18 cm above the bed. For test numbers 1-3, the coal feed was 75 g/min, while in test numbers 4 and 5, the coal feed rate was 40 g/min.

Table III. Exhaust Gas Compositions and Above-Bed Temperatures for Non-Pulsating Tests.

Test Number	$\alpha$	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)	T <sub>1</sub> (C)
1	0.5	10.82	0.80	278	1412	6.50	994
2	0.5	10.10	1.01	199	1462	7.30	1082
3	0.5	5.15	0.35	114	831	14.77	1005
4	0.5	7.96	0.20	143	967	11.85	893
5	0.5	9.58	0.29	170	954	11.45	892
2	0.7	9.48	0.32	242	1064	8.76	1027
3	0.7	5.99	0.33	136	801	13.83	1034
4	0.7	6.83	0.10	125	1041	13.38	862
5	0.7	9.27	0.18	193	873	11.86	892
3	1.0	6.44	0.18	177	745	13.64	982
4	1.0	6.91	0.27	164	996	14.16	853
5	1.0	6.56	0.14	212	737	12.98	854
4	1.1	6.25	0.07	143	1043	15.15	860
5	1.1	NA	0.10	220	770	12.71	899

As shown in Table III, there is considerable variation in the measured values from one test to another for the same air/fuel ratio. This is due largely to the varying amounts of partially burned coal which fell through and around the periphery of the coal bed during the non-pulsating tests. Thus the effective air/fuel ratios varied considerably among each group of tests segments with the same

nominal air/fuel ratio. Furthermore, the effective air/fuel ratios were always higher than the nominal values shown in Table III. For this reason it was found to be more meaningful to plot the measured values of  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$  and  $\text{SO}_2$  concentrations as a function of the  $\text{O}_2$  concentration rather than the air/fuel ratio. The amount of residual oxygen remaining in the exhaust gases is a function of the both the effective air/fuel ratio and the combustion efficiency. Plots of the concentrations of these four species as a function of residual oxygen concentration are shown in Figures 13 through 16.

The data shown in Figure 13 reveals that measured carbon dioxide concentrations for both pulsating and non-pulsating combustion are nearly linearly related to the residual oxygen concentration. For non-pulsating combustion,  $\text{CO}_2$  concentrations ranged from about 5 percent to about 11 percent, while the corresponding residual oxygen concentrations varied from about 15 percent to about 7 percent. Some of the scatter in the non-pulsating data results from differences in the air/fuel ratios and coal feed rates for the different tests. For the pulsating tests, air/fuel ratios ranged from 0.6 to 1.5. The  $\text{CO}_2$  concentrations for pulsating combustion were much higher with correspondingly lower residual  $\text{O}_2$  concentrations. The pulsating tests with the largest concentrations of residual oxygen corresponded to those with the largest amounts of excess air. These results show that the combustion efficiency is much lower under non-pulsating conditions, indicating incomplete combustion of the coal.

The carbon monoxide concentrations measured under non-pulsating combustion conditions are shown in Figure 14. Although there is considerable scatter in the  $\text{CO}$  data, there is a definite trend of decreasing  $\text{CO}$  concentration with increasing residual oxygen for the non-pulsating tests. Similar results were obtained for pulsating combustion, but the corresponding residual oxygen levels were much lower due to the higher combustion efficiency. The decrease in  $\text{CO}$  concentration with increasing residual  $\text{O}_2$  levels reflects the gas

phase oxidation of CO to CO<sub>2</sub> in the region above the coal bed when ample oxygen is present.

The nitrogen oxides emissions measured under non-pulsating combustion conditions are shown in Figure 15. These data follow a definite trend of decreasing NO<sub>x</sub> concentration with increasing O<sub>2</sub> concentration. Furthermore if a linear curve fit for the non-pulsating data is extended to very low residual oxygen levels, it agrees well with the pulsating combustion data for air/fuel ratios between 0.6 and 1.1, which is approximately the same range of  $\alpha$  used in the non-pulsating tests. For this range in  $\alpha$  the residual oxygen levels are a good measure of combustion efficiency, since little or no excess air is present. It thus appears that as the combustion efficiency increases, as evidenced by the decrease in residual oxygen, the production of nitrogen oxides from fuel-bound nitrogen increases.

The non-pulsating data presented in Figure 15 also show a significant increase in NO<sub>x</sub> production with increasing primary air/fuel ratio. For non-pulsating combustion under stoichiometric conditions and large residual O<sub>2</sub> levels (i.e., low combustion efficiency), NO<sub>x</sub> concentrations averaged about 180 ppm, which decreased to about 115 ppm at an air/fuel ratio of about 0.5. The pulsating data for air/fuel ratios above 1.1 also exhibit this trend of increasing NO<sub>x</sub> emissions with increases in excess air. These results are consistent with the hypothesis that most of the NO<sub>x</sub> is produced from fuel nitrogen and the amount produced is dependent on the availability of oxygen in the primary combustion zone. The NO<sub>x</sub> concentrations under non-pulsating combustion at high residual O<sub>2</sub> (low combustion efficiency) were less than half (stoichiometric) to a fourth ( $\alpha = 0.5$ ) of those produced under pulsating conditions with very low residual O<sub>2</sub> (high combustion efficiency).

Figure 16 shows the exhaust gas sulfur dioxide concentrations measured in both non-pulsating and pulsating tests as a function of residual oxygen concentration. For substoichiometric burning in the primary combustion zone, there is a pronounced trend of decreasing

SO<sub>2</sub> emissions with increasing residual O<sub>2</sub> concentrations (decreasing combustion efficiency). For the non-pulsating tests under stoichiometric and excess air conditions, the scatter in the data is large, but the SO<sub>2</sub> emissions appear to be somewhat larger than in the corresponding substoichiometric tests. The SO<sub>2</sub> data for the pulsating tests, which follow closely a straight line curve fit, fall below the extension of the linear curve fit for the substoichiometric non-pulsating data. This is due partially to the fact that the largest SO<sub>2</sub> values shown in Figure 16 represent nearly complete conversion of the sulfur in the coal to sulfur dioxide.

For test number 3 in Table III, two test segments were run with air staging at 20 cm above the bed under non-pulsating combustion conditions. The first test segment was conducted at a primary air/fuel ratio of 0.7, while the second test segment was conducted at  $\alpha_1 = 0.5$ . The results of these tests showed that carbon dioxide and residual oxygen levels in the exhaust were not significantly affected by air staging. On the other hand carbon monoxide levels were drastically reduced by air staging, indicating that some of the combustion efficiency was recovered by nearly complete combustion of the CO formed in the primary combustion zone. However the CO apparently was only a small fraction of the coal which did not burn in the primary zone. It is suspected that most of the incompletely burned material under non-pulsating conditions was fixed carbon in the coal which was lost with the ash which fell through the bed. For non-pulsating tests with air staging, the NO<sub>x</sub> emissions were increased. For example, at  $\alpha = 0.7$ , air staging increased the NO<sub>x</sub> concentration from 135 ppm to 205 ppm, which was larger than that produced under stoichiometric conditions in the primary zone without air staging. A similar result was obtained for  $\alpha = 0.5$ . Since this increase occurred in the secondary combustion zone where fuel-bound nitrogen is not expected to be present, it was probably due to thermal NO<sub>x</sub> production.

## FUTURE WORK

The investigation of methods to reduce  $\text{NO}_x$  emissions from the Rijke pulse combustor will be continued during the next quarter. A series of air staging tests will be conducted with total air/fuel ratios greater than unity. A series of fuel staging experiments will also be done where propane is injected at various locations in the combustor. In some of these experiments, a small amount of propane will be introduced into the primary air stream sufficiently far upstream of the coal bed to allow thorough mixing with the air before reaching the primary combustion zone. The quantity of propane introduced will be small to prevent ignition of the mixture before it reaches the primary combustion zone. These tests are based on the hypothesis that the propane will compete with the nitrogen for the available oxygen in the primary combustion zone which will reduce the nitrogen oxides emissions. In other tests, the primary combustion zone will be operated with excess air and propane will be burned in a stoichiometric zone downstream of the coal bed. These tests, which are similar to fuel staging methods used in steady combustors, are based on the theory that hydrocarbon radicals formed by the combustion of the propane reduce the  $\text{NO}_x$  produced in the primary zone to nitrogen ( $\text{N}_2$ ). Only a limited number of fuel staging tests will be conducted, however, since a complete evaluation of fuel staging is beyond the scope of this project.

Investigation of the reduction of sulfur dioxide emissions in the Rijke pulse combustor by addition of sorbent materials will begin in the next quarter. For the sorbent addition experiments, limestone or dolomite will be either mixed with the coal and delivered by the coal feed system or injected in finely pulverized form through the secondary air injector. In the latter method, the pulverized sorbent material is delivered from a hopper by a vertical auger into the air entrainment system. This consists of a small venturi supplied by low pressure air. The auger feeds the sorbent into the throat of the venturi where the high air velocity and low pressure disperses the sorbent particles into the air stream. The sorbent particles are then

carried through a stainless steel line to the radial injector head located just above the coal bed. The sorbent particles then mix with the combustion gases and react with the sulfur dioxide as they are carried out with the exhaust gases. In the sorbent addition experiments, the dependence of SO<sub>2</sub> formation upon the method of sorbent addition (mixed with coal or injected above bed), type of sorbent (limestone or dolomite), Ca/S molar ratio, and amount of excess air will be determined.

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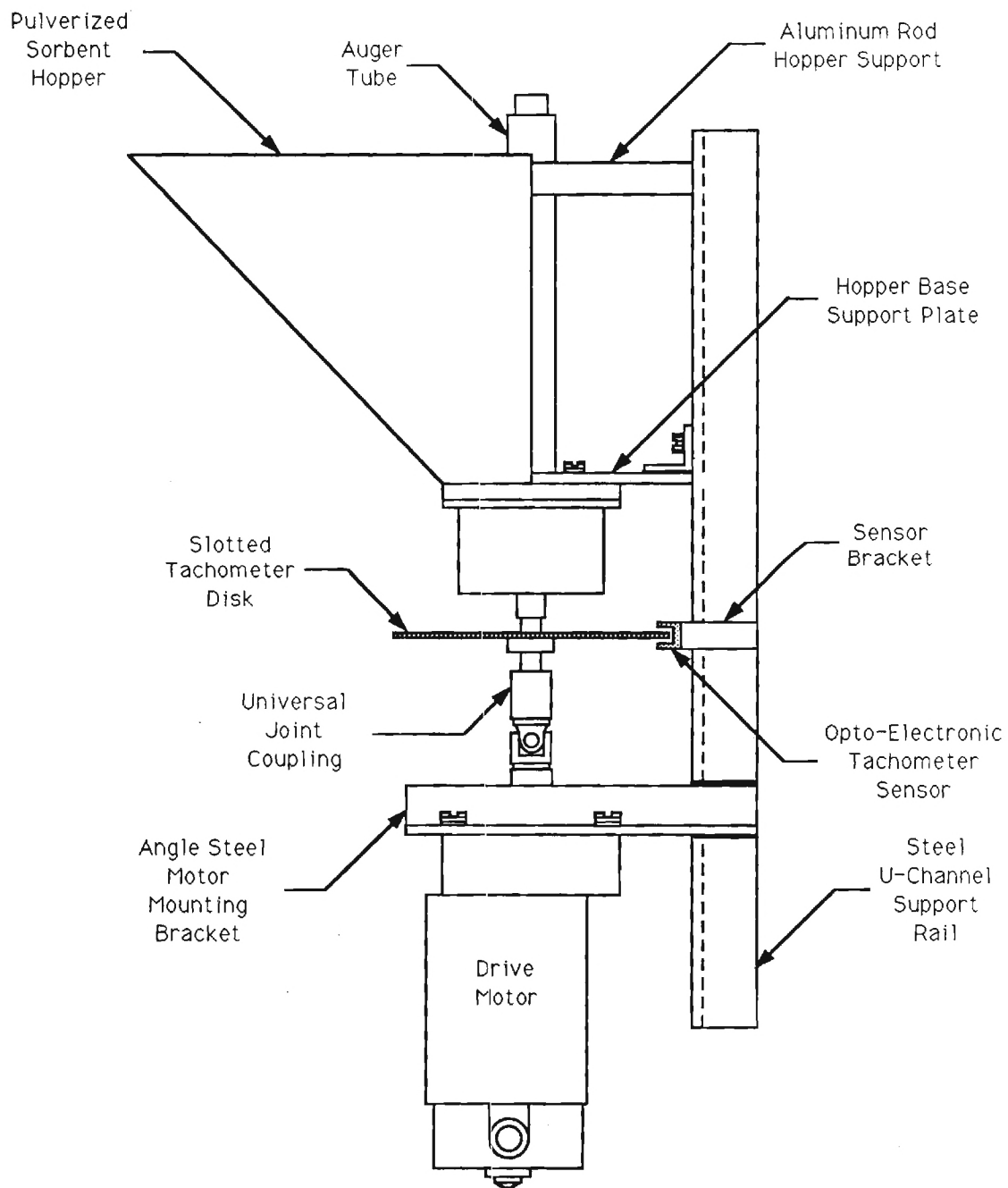


Figure 1. Pulverized Sorbent Feed Assembly

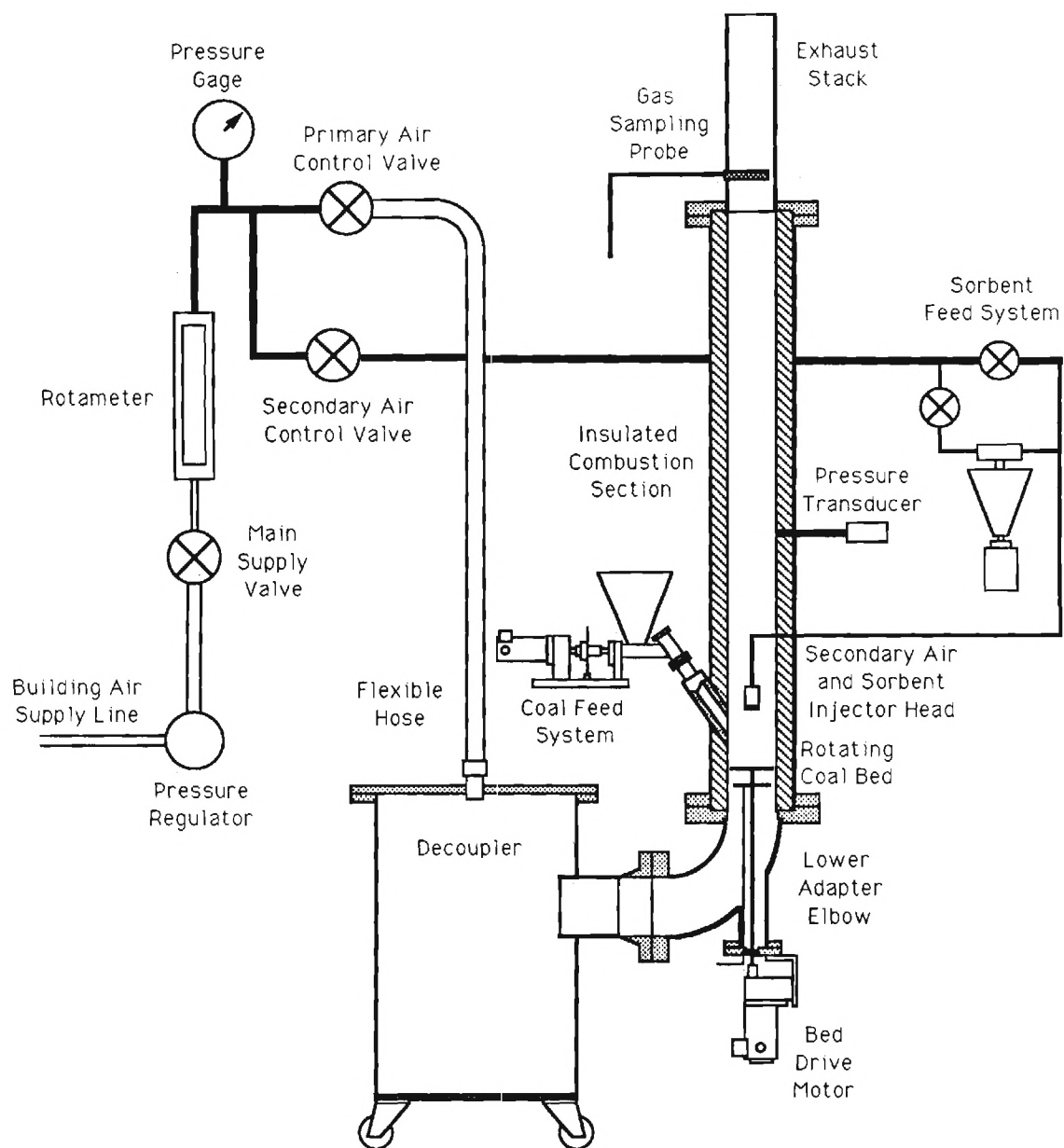


Figure 2. Rijke Pulse Combustor and Auxiliary Systems

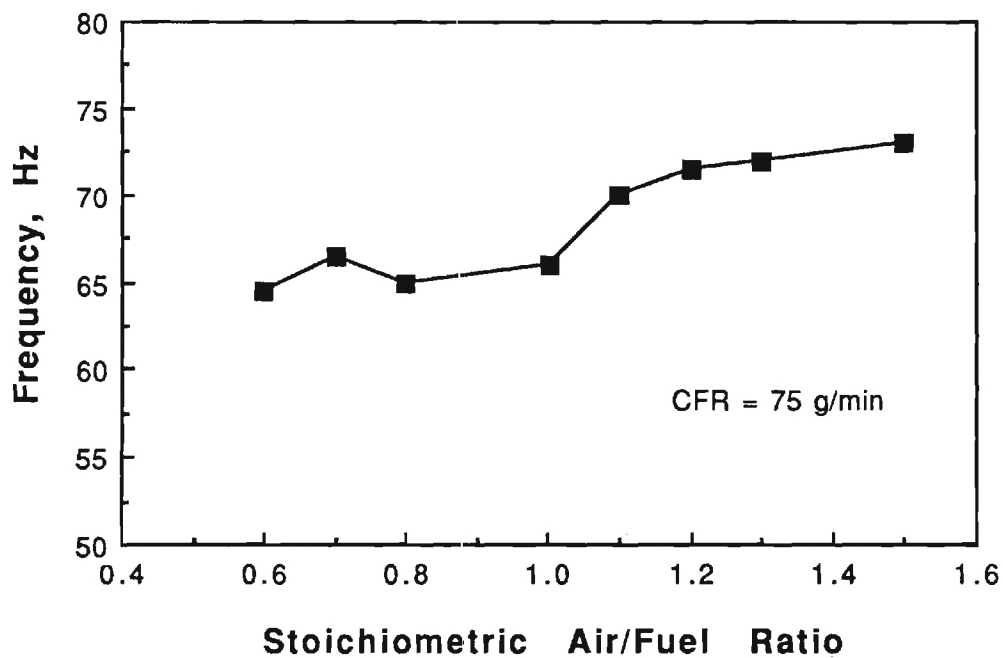
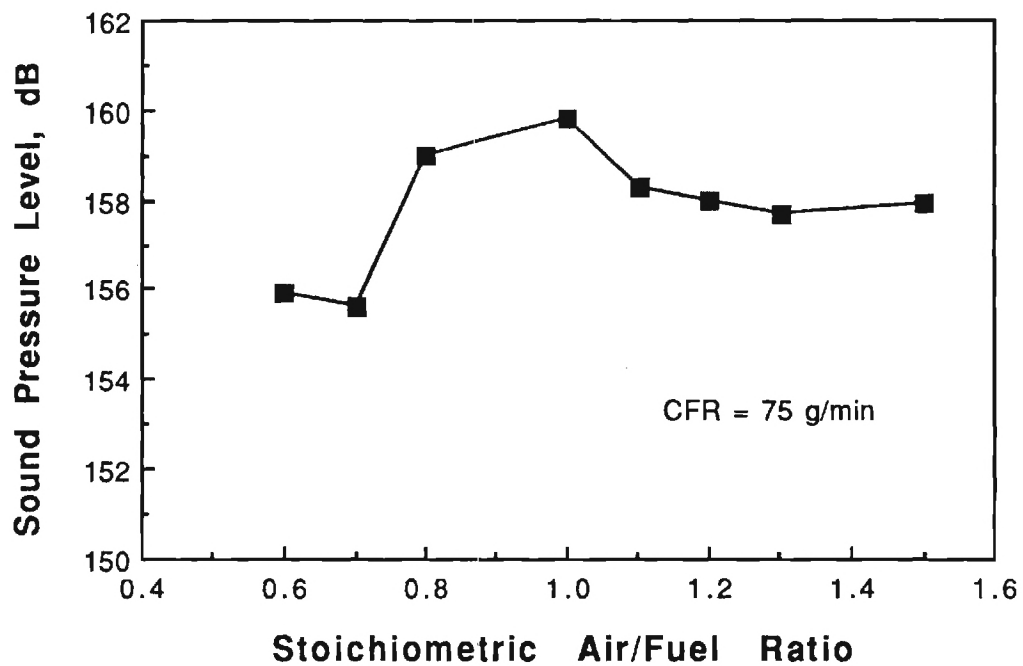


Figure 3. Dependence of Sound Pressure Levels and Frequencies Upon the Air/Fuel Ratio for Baseline Tests of the Rijke Pulse Combustor.

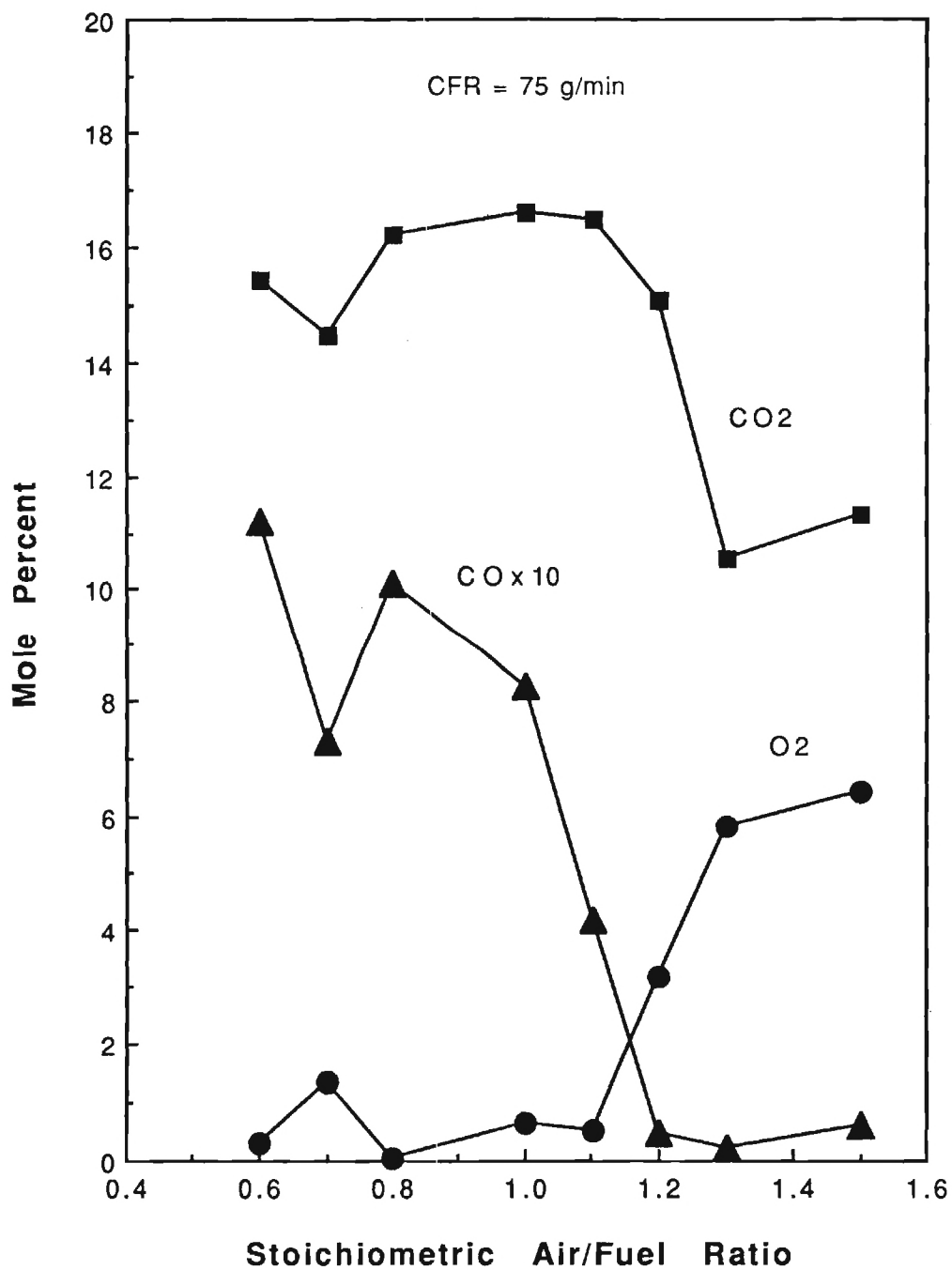


Figure 4. Effect of Air/Fuel Ratio Upon the Concentrations of Carbon Dioxide, Carbon Monoxide, and Residual Oxygen in the Exhaust Gases for Baseline Tests of the Rijke Pulse Combustor.

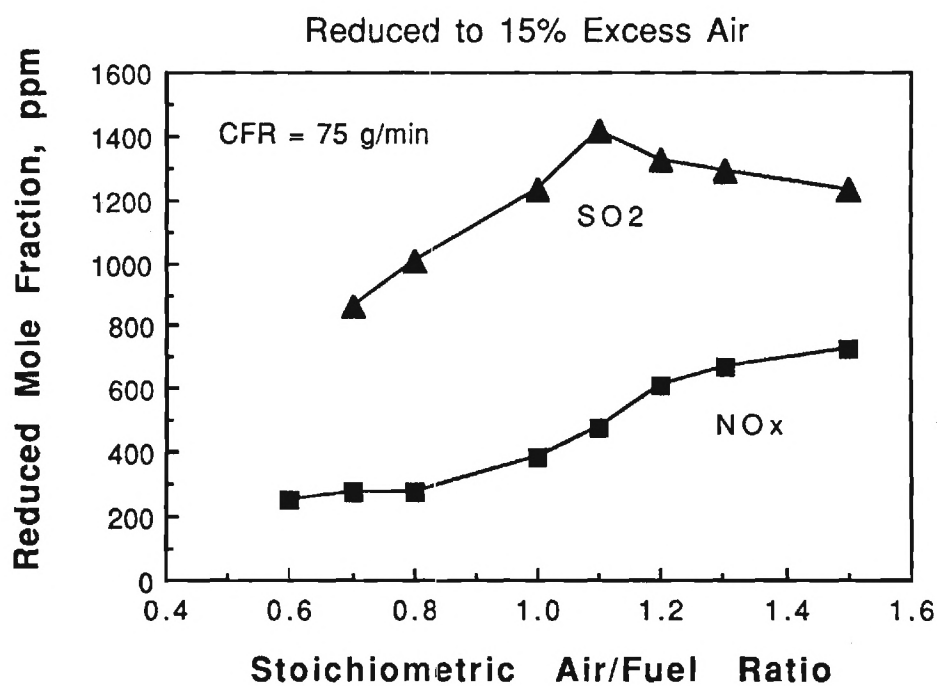
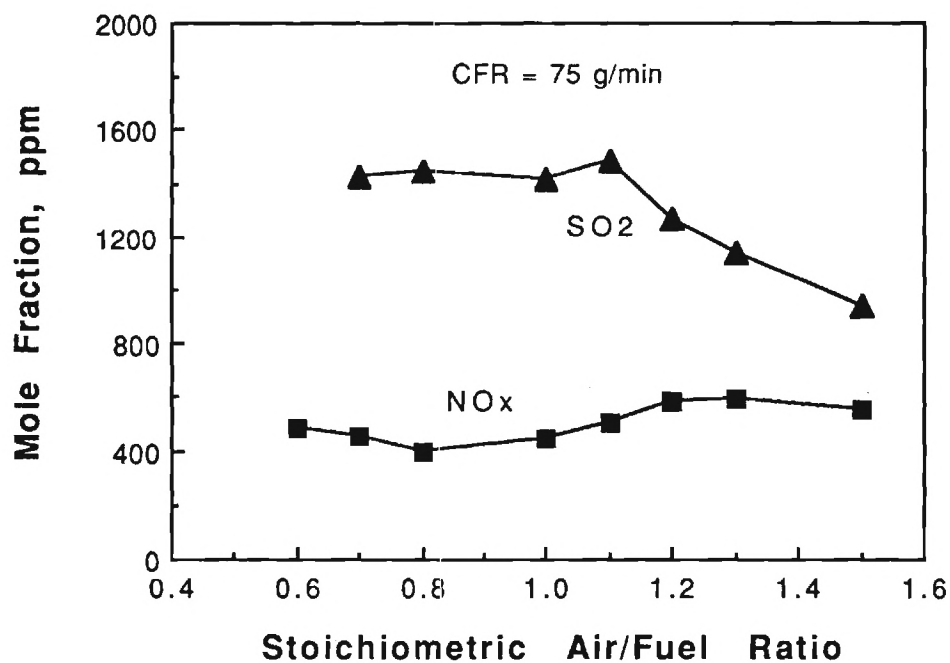


Figure 5. Effect of Air/Fuel Ratio Upon the Concentrations of Nitrogen Oxides and Sulfur Dioxide in the Exhaust Gases for Baseline Tests of the Rijke Pulse Combustor.

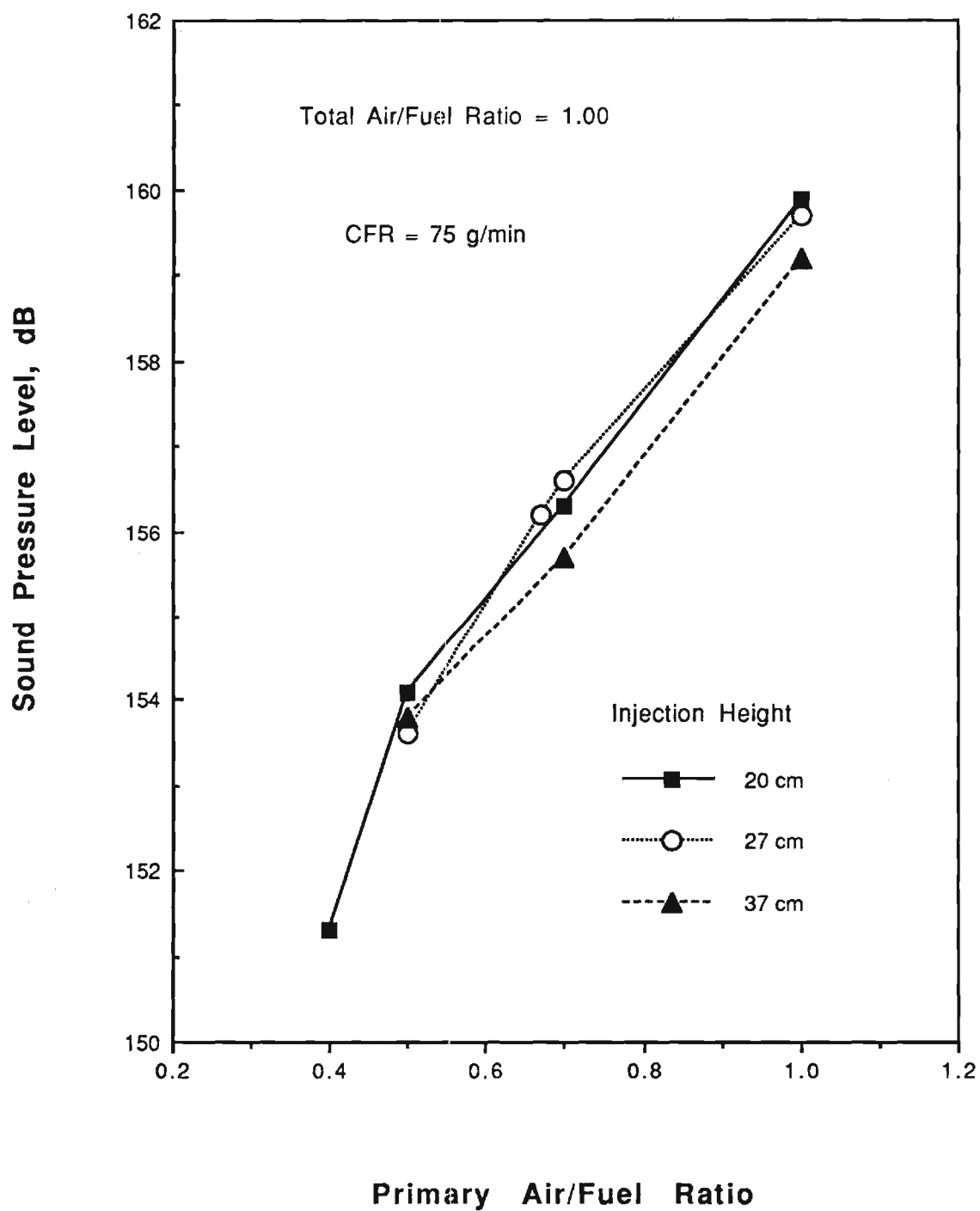


Figure 6. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Amplitude of the Pulsations in the Rijke Pulse Combustor.

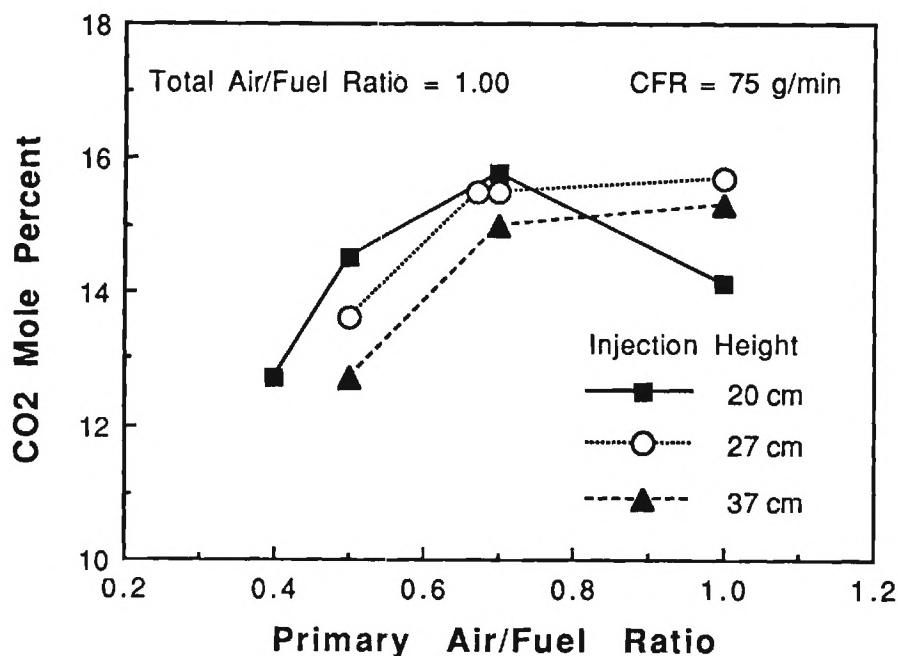


Figure 7. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Carbon Dioxide in the Exhaust Gases from the Rijke Pulse Combustor.

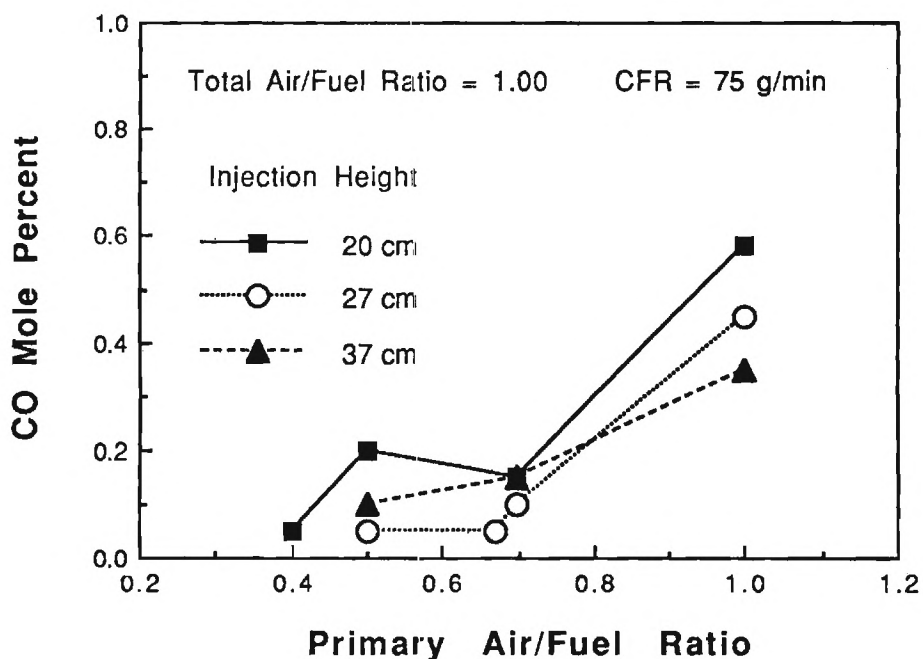


Figure 8. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Carbon Monoxide in the Exhaust Gases from the Rijke Pulse Combustor.

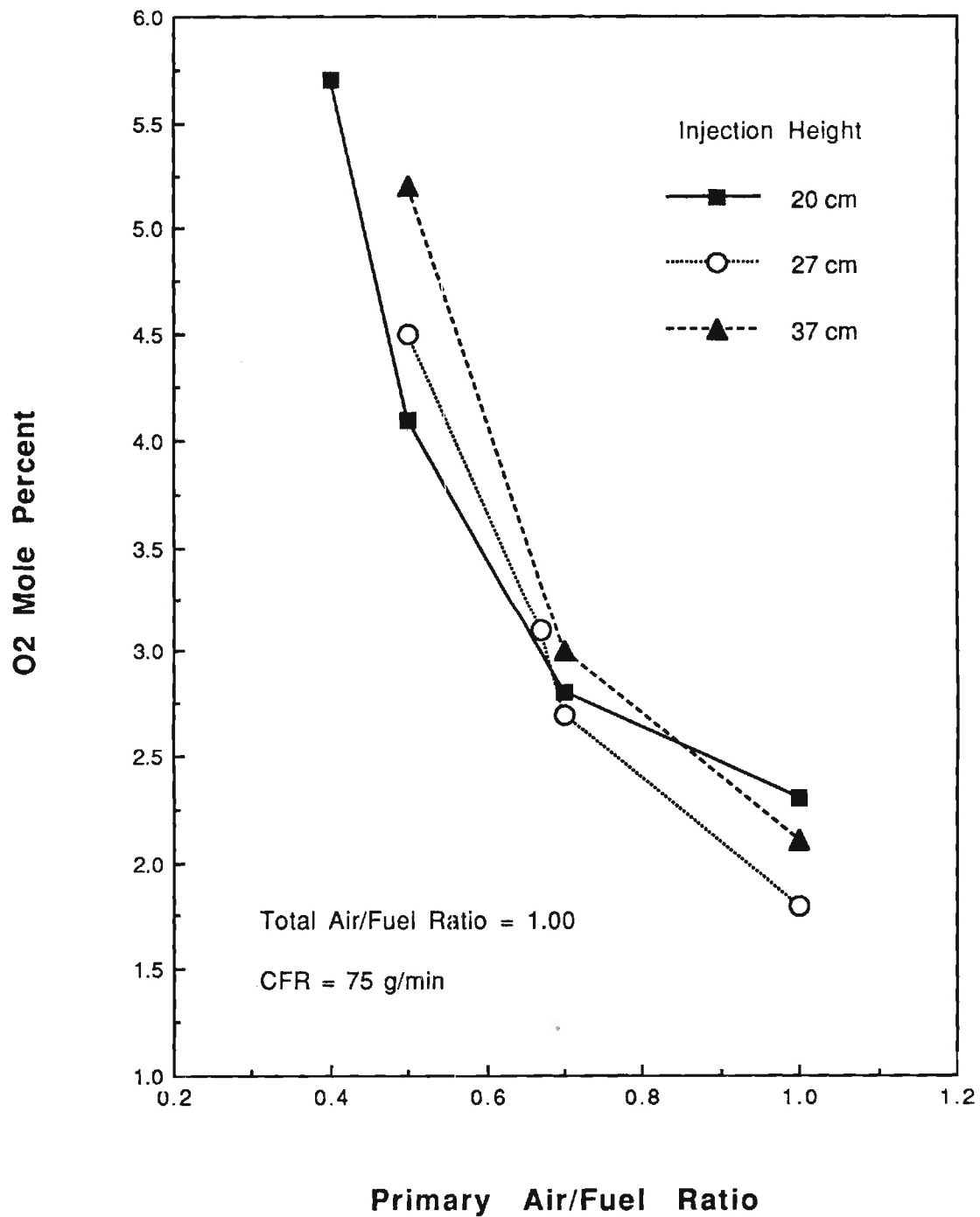


Figure 9. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Residual Oxygen in the Exhaust Gases from the Rijke Pulse Combustor.

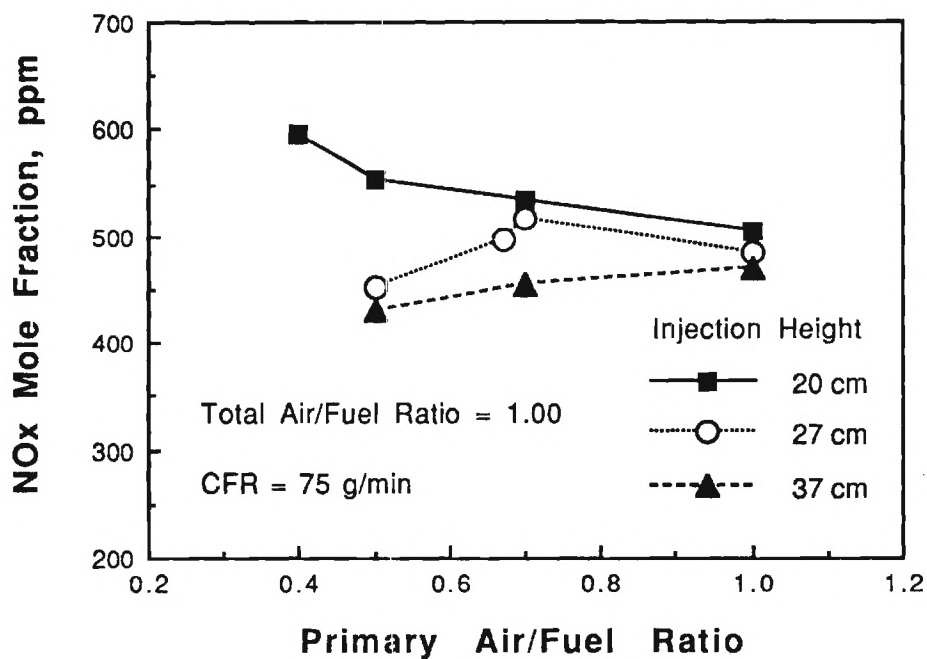


Figure 10. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Nitrogen Oxides Emissions from the Rijke Pulse Combustor.

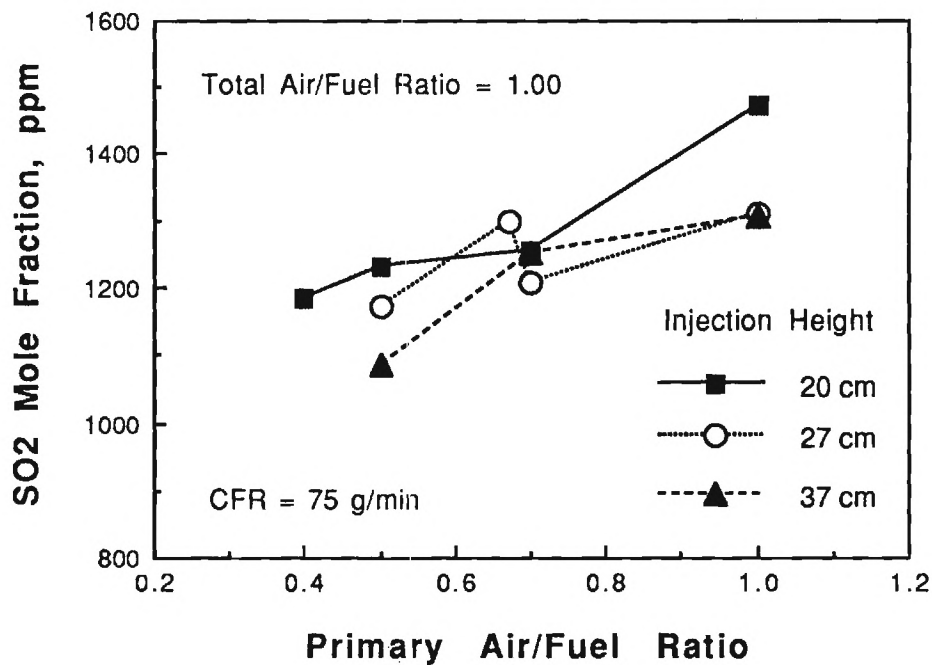


Figure 11. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Sulfur Dioxide Emissions from the Rijke Pulse Combustor.

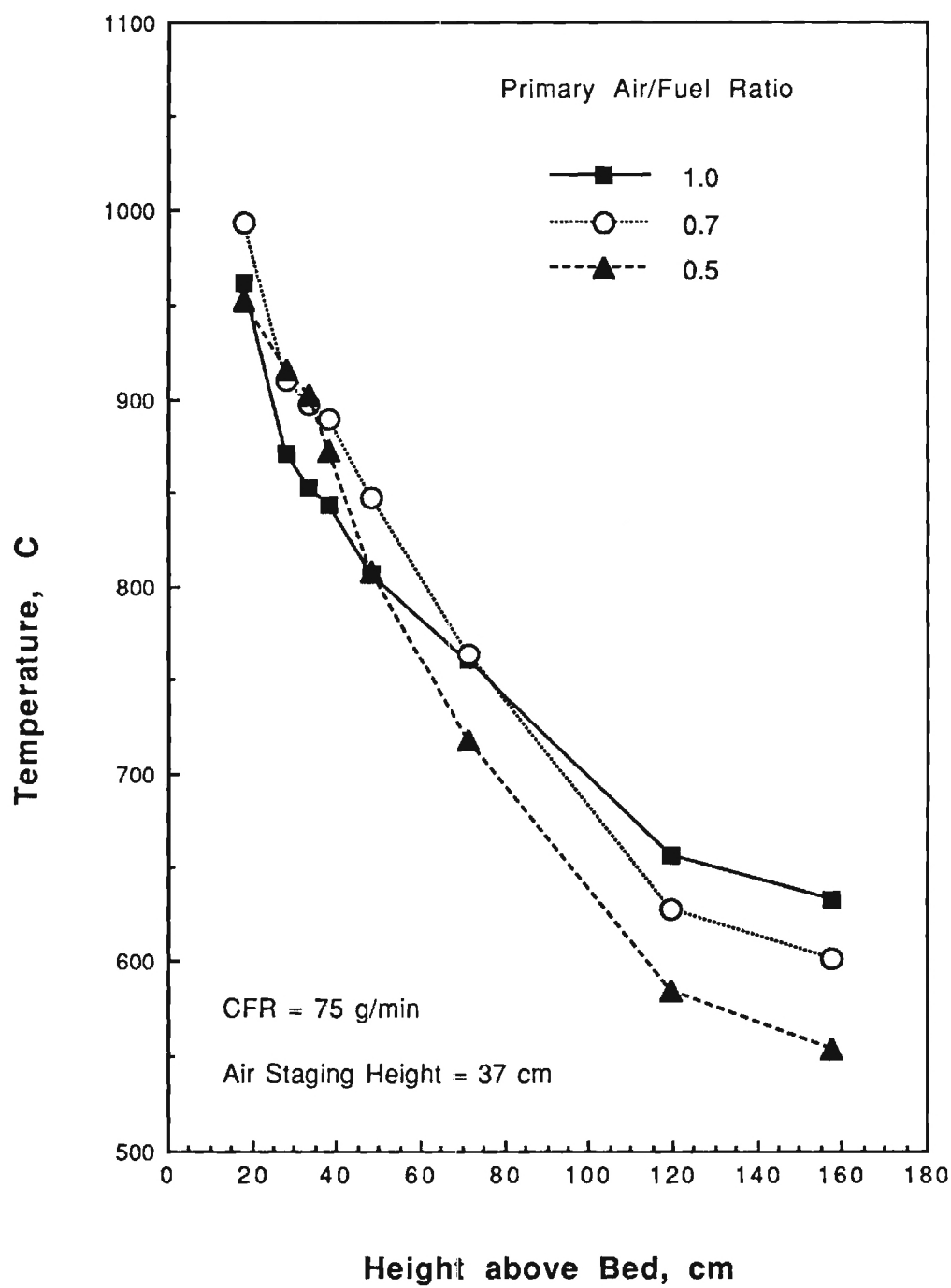


Figure 12. Effect of Air Staging on the Gas Temperature Distributions Downstream of the Coal Bed.

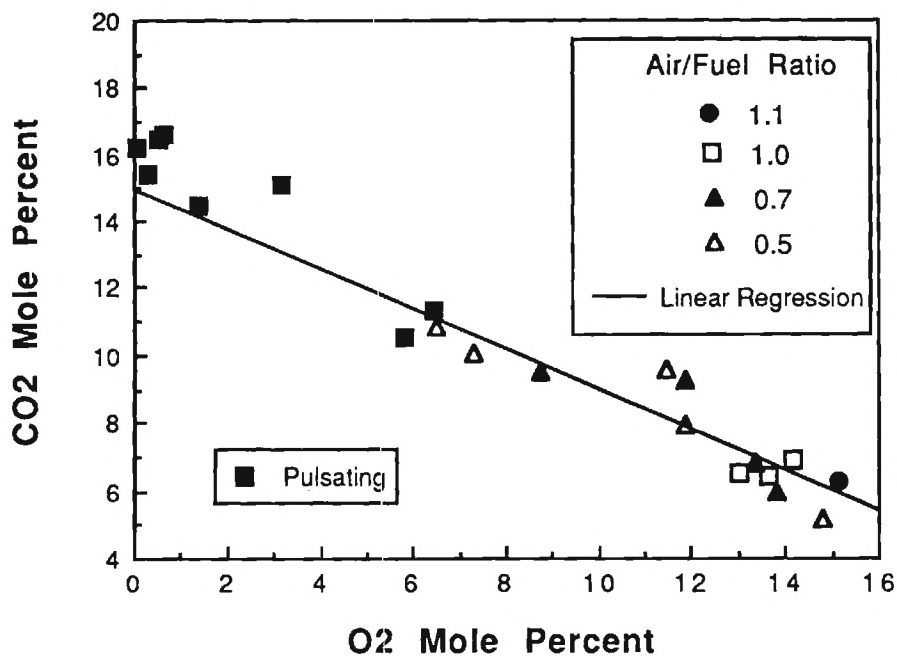


Figure 13. Comparison of Exhaust Carbon Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

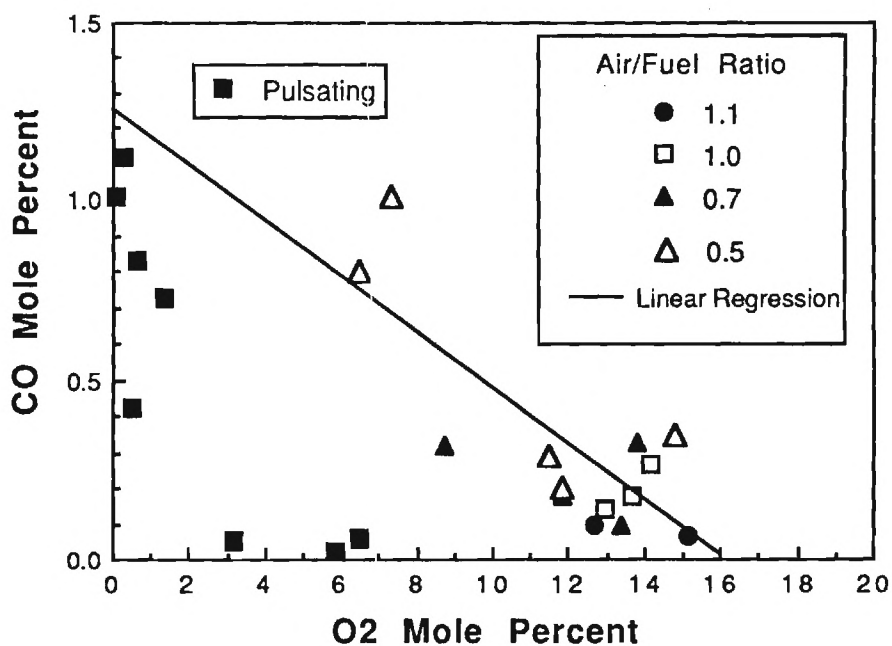


Figure 14. Comparison of Exhaust Carbon Monoxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

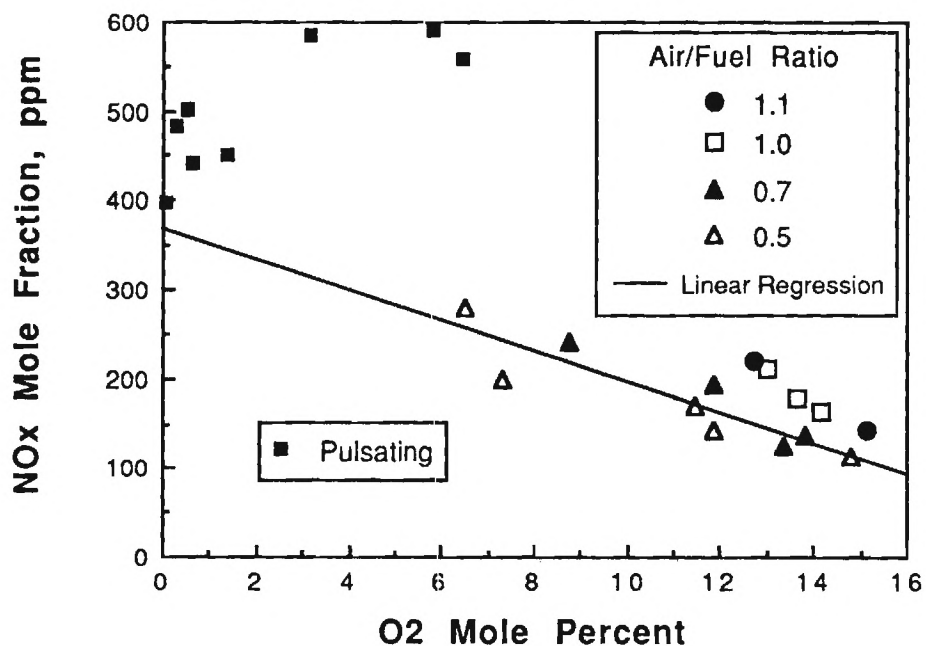


Figure 15. Comparison of Exhaust Nitrogen Oxides Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

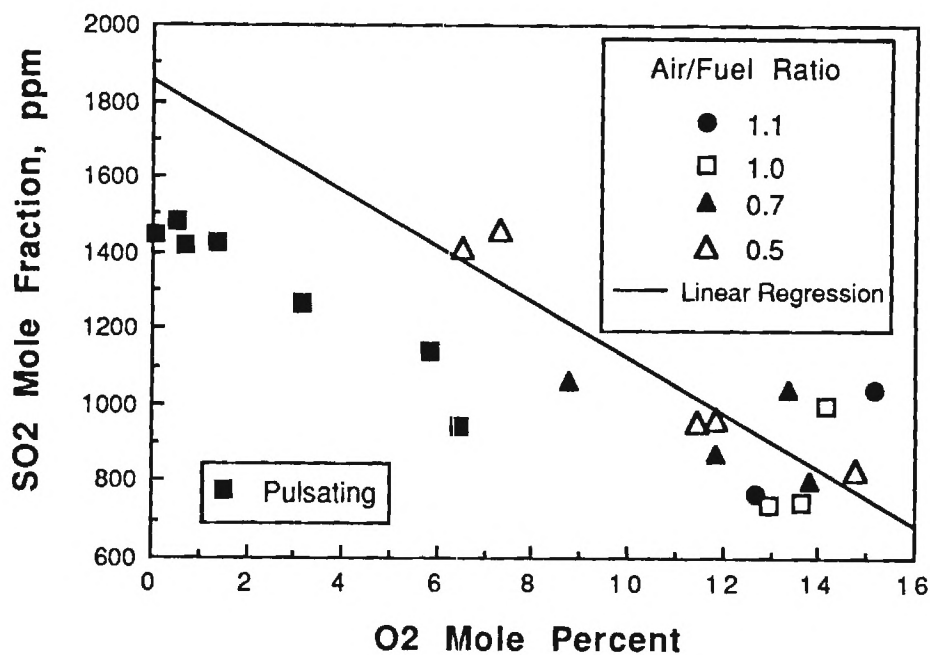


Figure 16. Comparison of Exhaust Sulfur Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

**REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
FROM COAL BURNING PULSE COMBUSTORS**

Quarterly Technical Progress Report  
for the Period April 1, 1990 - June 30, 1990

By

E. A. Powell and B. T. Zinn

August 1990

Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy  
Office of Fossil Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania 15236

By

School of Aerospace Engineering  
Georgia Tech Research Corporation  
Georgia Institute of Technology  
Atlanta, GA 30332

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## **COAL PULSE COMBUSTION RESEARCH**

**Quarterly Technical Progress Report for the Period  
April 1, 1990 - June 30, 1990**

**Prepared by**

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**August 1990**

**Technical Project Officer - Perry Bergman**

**Prepared for**

**United States Department of Energy  
Pittsburgh Energy Technology Center  
Pittsburgh, Pennsylvania**

**Under Contract No. DE-FG22-88PC88918**

## ABSTRACT

Work accomplished during the seventh quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

A second series of air staging tests was conducted to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the  $\text{NO}_x$  emissions. This second group of tests was conducted with total dimensionless air/fuel ratios ranging from 1.1 to 1.4. For these air staging tests, values of each of the measured quantities were obtained as a function of the total air/fuel ratio, with the primary air/fuel ratio ranging from 0.6 to 0.9. The secondary air was injected at a height of 52 cm above the bed. The air staging  $\text{NO}_x$  data was compared with the baseline data obtained without air staging. The results indicated that air staging yielded a very significant reduction in  $\text{NO}_x$  concentrations when expressed on a zero percent oxygen basis. These reductions in  $\text{NO}_x$  emissions, which were small to modest for a primary air/fuel ratio of 0.9 and a total air/fuel ratio of 1.1, increased significantly as the total air/fuel ratio was increased. Reducing the primary air/fuel ratio from 0.9 to 0.8 resulted in a significant further reduction in  $\text{NO}_x$  emissions, but little additional reduction in  $\text{NO}_x$  occurred for lower primary air/fuel ratios. For a primary air/fuel ratio of about 0.7, the reduction in  $\text{NO}_x$  exhaust concentration due to air staging ranged from about 48 percent at a total air/fuel ratio of 1.1 to about 56 percent for a total air/fuel ratio of 1.4.

Work began on the investigation of the reduction of sulfur dioxide emissions by the injection of sorbent materials into the Rijke pulse combustor. A pulverized dolomitic limestone material containing 24 percent calcium and 6 percent magnesium was used. The particle size of this material ranged from 0.1 mm to about 1.0 mm. Initially, difficulties were encountered in feeding and dispersing this material into the combustor. This required extensive modification of the limestone auger feed system and the air entrainment system. The auger was mounted horizontally, and a vibrator was installed on the hopper to ensure a continuous and constant feed rate of sorbent into the air entrainment system. The hopper was pressurized to overcome an air blow-back problem from the air entrainment system. Two series of preliminary tests were conducted with limestone addition. In these tests primary air/fuel ratios ranged from 0.8 to 1.6, and air staging was not used. For air/fuel ratios of 1.0 and Ca/S molar ratios between 2.4 and 4.2, little or no reduction in  $\text{SO}_2$  emissions was obtained. Increasing the air/fuel ratio to 1.2 for the same Ca/S ratios resulted about a 20 percent reduction in the exhaust  $\text{SO}_2$  concentration. However in these preliminary tests, the residence time of the sorbent particles, oxygen availability in the reaction zone, and reaction temperature were probably not in the optimum range for sulfur dioxide capture.

## INTRODUCTION

The following report summarizes work done under DOE Grant No. DE-FG-88PC88918 during the period April 1, 1990 through June 30, 1990. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

The following work will be described in this report: (1) a second series of air staging tests to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the  $\text{NO}_x$  emissions, (2) continued development of the sorbent feed system, and (3) preliminary tests with limestone addition for reducing  $\text{SO}_2$  emissions. The report will conclude with projected work to be accomplished during the remaining two months of the project.

## AIR STAGING TESTS

A second group of air staging tests was conducted during the report period. Unlike the first series of air staging tests, in which the final air/fuel ratio was equal to one, this second group of tests was conducted with total air/fuel ratios greater than one. The secondary air was also injected higher above the bed (52 cm) than in the previous group of air staging tests. This injection height was chosen based on data from the earlier tests which indicated that  $\text{NO}_x$  emissions decreased with increasing injection height (see Ref. 1). In this series, as in the previous one, the coal feed rate was 75 g/min. A total of 16 tests was conducted in this series, each consisting of four or five segments lasting about five minutes each. In each test the primary air/fuel ratio was fixed, while the amount of secondary air and hence the total air/fuel ratio was varied stepwise from 1.1 to 1.4. Tests were conducted for primary air/fuel ratios of 0.9, 0.8, 0.7 and 0.6. As in the previous tests, measurements of sound pressure levels, frequencies, and gas compositions ( $\text{CO}_2$ , CO,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and gas temperatures were made. However the CO and  $\text{SO}_2$  data are

not relevant to the issue of  $\text{NO}_x$  reduction, and they are not included in the results presented herein.

The results of the air staging tests are summarized in Tables I through III and in Figures 1 through 4. The individual test data are given in Table I for primary dimensionless air/fuel ratios of 0.9 and 0.8. Each set of values of sound pressure level (SPL), mole fractions of carbon dioxide ( $\text{CO}_2$ ), oxygen ( $\text{O}_2$ ), and nitrogen oxides ( $\text{NO}_x$ ), and the combustion efficiencies presented in Table I are the time averages over the appropriate test segment in a single air-staging test. For a given primary air/fuel ratio,  $\alpha_1$ , two to four test segments were conducted for each value of the total air/fuel ratio,  $\alpha_t$ . The corresponding time averages for primary air/fuel ratios of 0.7 and 0.6 are given in Table II. The  $\text{NO}_x$  emissions data has been reduced to a 0% oxygen basis using the formula:

$$\text{NO}_x (0\% \text{ O}_2) = [\text{NO}_x] / (1 - [\text{O}_2] / 0.21)$$

where

$[\text{NO}_x]$  = measured exhaust  $\text{NO}_x$  concentration in ppm

$[\text{O}_2]$  = measured  $\text{O}_2$  mole fraction in exhaust

The combustion efficiency  $\eta_c$  was calculated using the formula:

$$\eta_c = 0.217 + (0.173 [\text{CO}_2] + 0.049 [\text{CO}]) N_{td}$$

where

$[\text{CO}_2]$  = measured exhaust  $\text{CO}_2$  mole fraction

$[\text{CO}]$  = measured exhaust CO mole fraction

$N_{td}$  = total number of moles in exhaust, dry basis

Table I. Air Staging Data for Primary Air/Fuel Ratios of 0.9 and 0.8.

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	SPL (dB)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	NO <sub>x</sub> (0% O <sub>2</sub> ) (ppm)	Combustion Efficiency
0.9	1.1	158.1	16.3	2.95	420	0.99
0.9	1.1	158.9	14.8	4.77	591	0.92
0.9	1.1	159.1	14.8	3.33	497	0.92
0.9	1.1	156.1	14.5	4.90	549	0.90
0.9	1.2	158.6	13.6	6.35	642	0.92
0.9	1.2	157.6	15.3	4.19	401	1.01
0.9	1.2	156.6	14.1	5.42	480	0.94
0.9	1.2	158.5	13.5	5.15	532	0.92
0.9	1.3	156.9	13.3	6.19	439	0.96
0.9	1.3	157.2	13.5	6.11	469	0.97
0.9	1.3	158.9	13.1	5.53	505	0.95
0.9	1.4	157.3	11.7	7.65	457	0.92
0.9	1.4	158.6	NA	6.55	489	NA
0.8	1.1	155.7	15.9	2.82	341	0.97
0.8	1.1	159.4	14.7	3.34	318	0.92
0.8	1.1	157.2	14.0	4.16	316	0.88
0.8	1.2	158.7	15.2	3.38	331	1.00
0.8	1.2	155.6	13.6	4.88	350	0.92
0.8	1.2	156.3	12.5	6.07	372	0.86
0.8	1.3	158.3	14.2	4.55	348	1.01
0.8	1.3	156.1	11.4	6.92	369	0.86
0.8	1.3	156.1	11.6	7.11	377	0.87
0.8	1.4	158.3	12.7	6.34	363	0.98
0.8	1.4	155.9	9.6	8.74	389	0.81

Table II. Air Staging Data for Primary Air/Fuel Ratios of 0.7 and 0.6.

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	SPL (dB)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	NO <sub>x</sub> (0% O <sub>2</sub> ) (ppm)	Combustion Efficiency
0.7	1.2	157.0	13.4	4.76	350	0.91
0.7	1.2	157.2	12.4	5.68	302	0.86
0.7	1.3	156.5	13.2	5.42	369	0.95
0.7	1.3	156.8	12.9	5.93	336	0.94
0.7	1.4	156.5	12.8	6.25	361	0.99
0.7	1.4	156.3	12.6	6.44	383	0.98
0.6	1.1	152.7	15.3	3.57	360	0.94
0.6	1.2	153.2	12.4	5.99	335	0.86
0.6	1.2	153.1	12.3	6.07	343	0.86
0.6	1.2	156.4	11.8	6.33	328	0.84
0.6	1.3	156.2	12.4	6.16	365	0.91
0.6	1.3	152.4	12.7	6.15	386	0.93
0.6	1.4	155.9	13.1	5.32	384	1.01
0.6	1.4	152.7	14.5	4.93	414	1.09

For given air staging parameters (i.e.,  $\alpha_1$  and  $\alpha_t$ ) there were considerable variations in the efficiency of the overall combustion process as reflected in the variations in the exhaust concentrations of CO<sub>2</sub> and O<sub>2</sub>. There were also significant variations in sound pressure levels and NO<sub>x</sub> concentration for tests conducted with identical air staging parameters. The variations in the measured NO<sub>x</sub> concentrations are best seen in Figure 1 where the individual time averaged test data are shown. The largest data scatter occurred for the nominal primary air/fuel ratio of 0.9, while the scatter was much smaller for the lower  $\alpha_1$  values. This graph readily shows that the NO<sub>x</sub> emissions were significantly reduced as the primary air/fuel ratio was decreased from 0.9 to 0.8, but only slight improvements were obtained by further decreases in the primary air/fuel ratio.

Mean values of sound pressure levels, combustion efficiencies and exhaust NO<sub>x</sub> concentrations were also computed for each set of air staging parameters  $\alpha_1$  and  $\alpha_t$  by taking the arithmetic average of the appropriate values shown in Tables I and II. These mean values are given in Table III.

Table III. Averaged Air Staging Data.

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	Sound Pressure Level (dB)	Combustion Efficiency	NO <sub>x</sub> (0% Oxygen) (ppm)
0.9	1.1	158.1	0.93	514
0.9	1.2	157.8	0.95	514
0.9	1.3	157.7	0.96	471
0.9	1.4	158.0	0.92	473
0.8	1.1	157.4	0.92	325
0.8	1.2	156.9	0.93	351
0.8	1.3	156.8	0.91	365
0.8	1.4	157.1	0.90	376
0.7	1.2	157.1	0.89	326
0.7	1.3	156.7	0.95	353
0.7	1.4	156.4	0.99	372
0.6	1.1	152.7	0.94	360
0.6	1.2	154.2	0.85	335
0.6	1.3	154.3	0.92	376
0.6	1.4	154.3	NA	399

The mean NO<sub>x</sub> concentrations given in Table III were plotted as a function of the total dimensionless air/fuel ratio,  $\alpha_t$ , for each value of the primary dimensionless air/fuel ratio,  $\alpha_1$ . These averaged NO<sub>x</sub> data are shown in Figure 2 along with the baseline NO<sub>x</sub> concentrations obtained without air/staging. For the air staging data,

a linear regression curve fit is shown for each primary air/fuel ratio, while a quadratic curve fit (nonlinear regression) is shown for the baseline data. Comparison of the air-staging curves with the baseline curve reveals that air staging yielded a very significant reduction in  $\text{NO}_x$  concentrations when expressed on a 0% oxygen basis. These reductions in  $\text{NO}_x$  emissions, which were small to modest for the lowest total air/fuel ratio (1.1), increased significantly as the total air/fuel ratio was increased. Extrapolation of the linear regression lines to  $\alpha_t = 1.0$  shows that only small reductions or even increases ( $\alpha_1 = 0.9$ ) in  $\text{NO}_x$  emissions occur with air staging to final stoichiometric conditions, a result in agreement with the results presented in the previous report (Ref. 1). The largest reductions in  $\text{NO}_x$  occurred when going from no air staging (baseline) to air staging with a primary air/fuel ratio of 0.9. Significant further reductions in  $\text{NO}_x$  occurred with further reduction in the primary air/fuel ratio to 0.8, but little additional reduction in  $\text{NO}_x$  emissions was obtained with lower primary air/fuel ratios. Close examination of Figure 2 shows that the optimum primary air/fuel ratio for  $\text{NO}_x$  reduction is about 0.7. For this case the reduction in  $\text{NO}_x$  exhaust concentration due to air staging ranged from about 48 percent at  $\alpha_t = 1.1$  to about 56 percent at  $\alpha_t = 1.4$ .

The averaged sound pressure levels from Table III are plotted in Figure 3. For the air staging tests with primary air/fuel ratios of 0.7 to 0.9, sound pressure levels were generally about 2 to 4 decibels lower than those obtained without air staging (about 160 dB). This reduction in pulsation amplitude was expected since the combustion process no longer is completed at the optimum location in the Rijke tube (i. e., the point one fourth of the distance from the upstream end to the downstream end). With air staging, a significant fraction of the heat addition occurs in the region where the secondary air is injected, which is nearer to the midpoint of the tube. Even lower pulsation amplitudes, from 6 to 7 decibels lower than baseline levels, were obtained when the primary air/fuel ratio was 0.6.

The averaged combustion efficiencies from Table III are plotted in Figure 4. These efficiencies ranged from about 85 percent to 99 percent. Only for primary air/fuel ratios of 0.9 and 0.8 is the combustion efficiency lower for the lower primary air/fuel ratio for all total air/fuel ratios tested. Thus the combustion efficiency is significantly influenced by factors other than the pulsation amplitude, since sound pressure levels generally decrease with decreasing primary air/fuel ratio. One factor of considerable variability which influenced the combustion efficiency was the amount of unburned carbon in the refuse which fell through the rotating bed grid.

### SORBENT FEED SYSTEM

Two dolomitic limestone materials were obtained for use as sulfur capturing agents. Both are commercially available agricultural liming products used for reducing the acidity of soils. One of the materials is in a pelletized form with particle sizes between about 0.5 and 2 mm, while the other material is in finely pulverized form with most of the particle sizes between 0.1 mm and 1.0 mm. The mass median diameter of the pulverized limestone is 0.4 mm. The pelletized dolomitic limestone contains about 24% calcium and 8% magnesium, while the pulverized material consists of 24% calcium and 6% magnesium.

The pelletized material was found to be too coarse to pass through the auger feed and air entrainment system. This material is more suitable for mixing with the coal and introducing it into the combustor along with the coal using the coal feed system. On the other hand the pulverized limestone was found to be unsuitable for directly mixing with the coal. Because the limestone particles are much smaller than the coal particles, they tend to settle to the bottom of the hopper by falling through the spaces between the coal particles. Thus uniform delivery of the limestone at a fixed Ca/S ratio is impossible by this method.

Attempts were made to feed the pulverized dolomitic limestone into the air entrainment system. Two difficulties were encountered. First, after filling the hopper with limestone, the auger would feed for only about a minute before a cavity formed in the limestone around the entrance to the auger. This phenomenon, referred to as "bridging" or "rat-holing", is commonly encountered when attempting to transport finely pulverized materials. The second problem was that at the required air flow rates the pressure at the venturi throat was greater than atmospheric pressure, resulting in air "blowback" through the auger and out through the hopper. Of course during blowback conditions, it was impossible to feed limestone into the venturi. Because of design modifications needed to correct these two problems, the series of sorbent addition tests was delayed. However a few preliminary tests were conducted near the end of the quarter which will be described in the next section of this report.

In order to correct the "bridging" problem the limestone feed system was modified. The vertical auger configuration shown in Reference 1 was abandoned in favor of a horizontal auger configuration as shown in Figure 5. This replaced the originally vertical auger entrance aperture with one horizontally oriented. In the horizontal configuration gravity should be more effective in maintaining flow to the auger and preventing bridging. However, tests with the horizontal auger revealed that bridging was still a serious problem. These tests also showed that cavity formation could be prevented by manually stirring the limestone at the bottom of the hopper with a steel rod. This suggested that mechanical vibration of the entire limestone feed system could alleviate the bridging problem. A motor driven vibrator was obtained and mounted on one side of the limestone hopper as shown in Figure 5. The feed system was itself mounted on a separate stand so that it is free to vibrate and to eliminate transmission of vibrations to the combustor and other components.

In order to eliminate the "blowback" problem, the limestone entrainment venturi was modified to have an adjustable throat area. This "venturi" serves as a transition from circular cross-section tubing to a rectangular cross-section entrainment section and back to circular tubing again. The rectangular cross-section is needed in order to give a flush fit with the exit end of the auger. To prevent the possibility of clogging, the minimum allowable throat area was about 0.8 mm. Tests indicated that reducing the throat area reduced the throat pressure to below atmospheric pressure in the absence of limestone, but the throat pressure became greater than atmospheric pressure when limestone was introduced into the venturi. This increased pressure, which again resulted in blowback through the auger and hopper, was due to the increased downstream resistance caused by the presence of the limestone particles. To prevent blowback the hopper was modified so that it could be pressurized. A steel cover plate was welded to the top of the hopper. A threaded pipe connection allowed filling of the hopper with limestone, after which an air supply line was connected. The dust seal bearing at the base of the auger shaft was also modified to allow pressurization to prevent dust blowback into the laboratory. Subsequent tests revealed that these modifications, which are also shown in Figure 5, successfully eliminated the blowback problem.

## **PRELIMINARY TESTS WITH LIMESTONE ADDITION**

Two series of preliminary tests with sorbent addition were conducted during the report period. The first series of tests was conducted before the modifications of the limestone feed system were completed, and the air entrainment system could not be used. Instead the limestone auger was temporarily arranged to feed the limestone directly into the coal delivery tube. Thus the limestone and coal were fed together directly onto the coal bed grid during this series of tests. The second series of tests was conducted after the modifications of the sorbent addition system were completed. The air entrainment system was utilized, and the limestone was injected into

the combustor just above the exit of the coal feed tube. In both series of tests the pulverized dolomitic limestone was used.

Each test in the first series was divided into two to five test segments. In the first test segment the combustor was operated in the pulsating mode for several minutes without sorbent addition. In subsequent test segments dolomitic limestone was added at rates corresponding to Ca/S mole ratios ranging from 2.4 to 4.2. The coal feed rate was 75 g/min for all of the tests. In most of the test segments the dimensionless primary air/fuel ratio was 1.0 with no secondary air injection (air staging). In the remaining test segments the primary air/fuel ratio ranged from 1.1 to 1.6, again without air staging. The gas sampling and analysis system was used to determine sulfur dioxide concentrations in the exhaust gases for all of the test segments. The results were reduced to a 0% oxygen basis in all cases.

The results of the first series of limestone addition tests are shown in Figures 6 and 7. In Figure 6, sulfur dioxide concentrations are shown for all test segments with dimensionless air/fuel ratios of 1.0 and 1.2. The SO<sub>2</sub> concentrations obtained with limestone addition can be compared with those obtained without limestone addition (Ca/S = 0). For the cases with  $\alpha = 1.0$ , there is no evidence in the data for SO<sub>2</sub> reduction when the limestone was added. For the cases with  $\alpha = 1.2$ , there appears to be a reduction of about 20% in SO<sub>2</sub> emissions when compared with the  $\alpha = 1.0$  case. In Figure 7, the effect of primary air/fuel ratio upon SO<sub>2</sub> concentrations are shown for a Ca/S mole ratio of 4.2. Here the individual data are plotted for all of these test segments along with a linear regression curve fit. This shows a definite trend of decreasing SO<sub>2</sub> emissions when the dimensionless air/fuel ratio is increased. This result can be explained by the fact that some residual oxygen is needed in order to complete the sulfur capture process; that is, to convert the SO<sub>2</sub> into CaSO<sub>4</sub>.

Three tests were conducted in the second series, where the limestone was injected into the combustor using the air entrainment system. Each test was divided into three test segments, with the first

test segment being conducted without limestone addition. In the other test segments, limestone was added with Ca/S ratios ranging from 3.6 to 8.0. In the first two tests the primary air/fuel ratio was 1.0, while a small amount of secondary air was needed for injection of the limestone. In the third test, the primary air/fuel ratio was 0.8. The coal feed rate was 75 g/min for all of the test segments. Measured SO<sub>2</sub> concentrations indicated that little or no reduction in SO<sub>2</sub> occurred as a result of the limestone injection even at the highest Ca/S ratio used.

There are three factors that are probably involved in the failure of the limestone addition to result in significant reduction in sulfur dioxide in these preliminary tests: residence time, oxygen availability, and reaction temperature. When the limestone was introduced through the coal delivery tube or through the air entrainment system, the larger limestone particles fell to the coal bed where the temperature was too high for effective sulfur dioxide capture, while the smallest particles were rapidly carried out with the flow of the exhaust gases. For adequate residence time for sulfur dioxide removal, the limestone particles should be of an intermediate size so that they neither fall to the bed nor are rapidly elutriated. Also the primary combustion zone should be provided with excess air to provide adequate residual oxygen needed for sulfur dioxide removal. Finally a means of temperature control in the region immediately above the bed is needed in order to maintain the gas temperature in the optimum range for sulfur dioxide capture.

### FUTURE WORK

The experimental work on the reduction of nitrogen oxides emissions by means of air staging has been completed. After additional analysis of the data, the final results will be presented in the Final Technical Report on this project. Also a paper describing these results will be prepared and submitted to a journal in the combustion field.

During the final two months of this project, additional tests will be conducted with modifications in the limestone addition procedure and operating parameters to determine if significant reductions in sulfur dioxide emissions can be obtained in the Rijke combustor. One of the modifications will be the installation of a water cooled coil extending from about 5 cm below the limestone injector to about 15 cm above the injector. These tests will all be conducted with excess air in the primary combustion zone in order to provide adequate oxygen for sulfur dioxide removal. Finally the limestone will be further pulverized to reduce the size of the larger particles and sieved to remove the smaller particles in order to obtain particles of about 0.5 mm in diameter.

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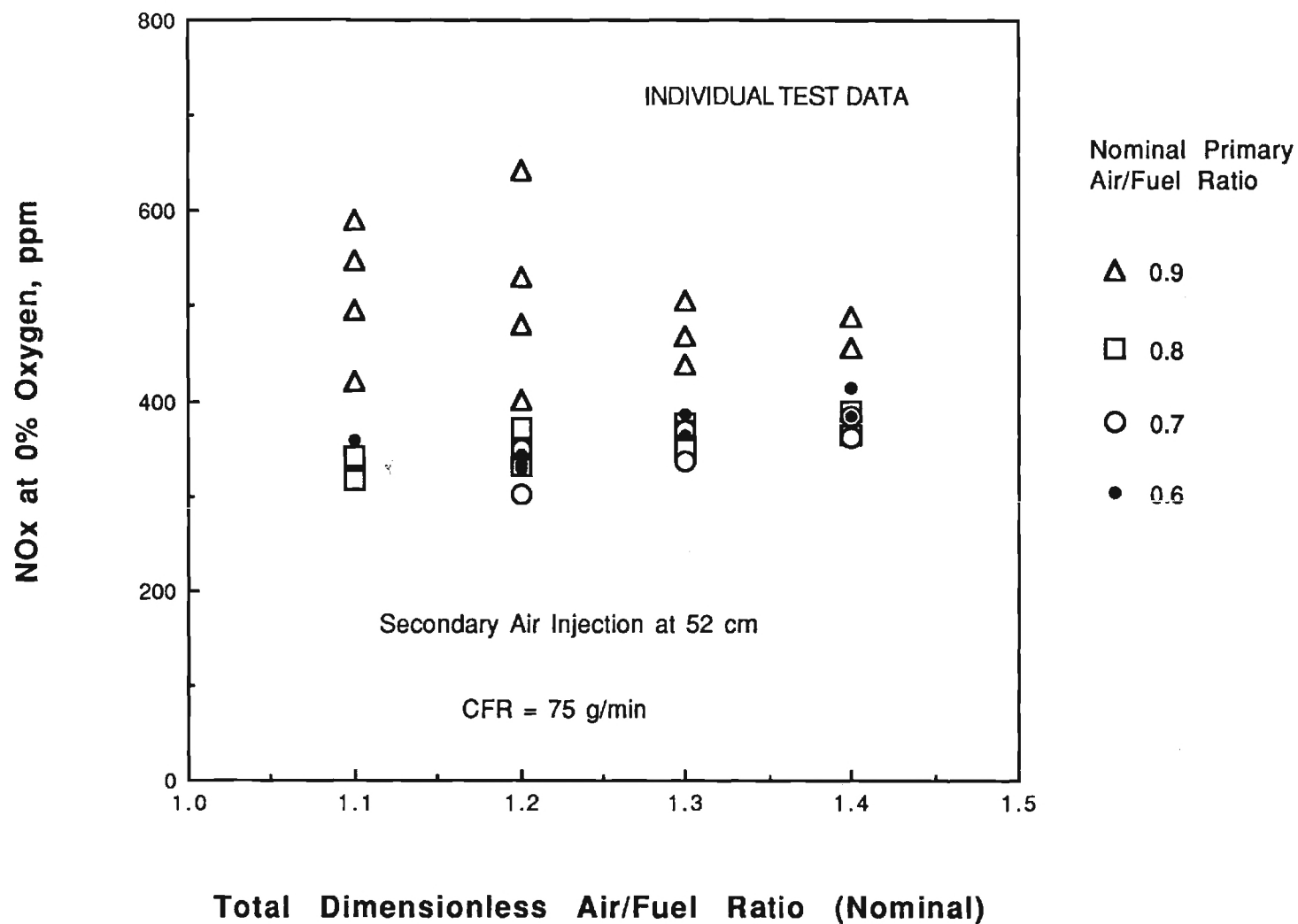


Figure 1. Individual Test Averages of Nitrogen Oxides Emissions for Air Staging Tests Showing the Effect of Total Air/Fuel Ratio and Primary Air/Fuel Ratio.

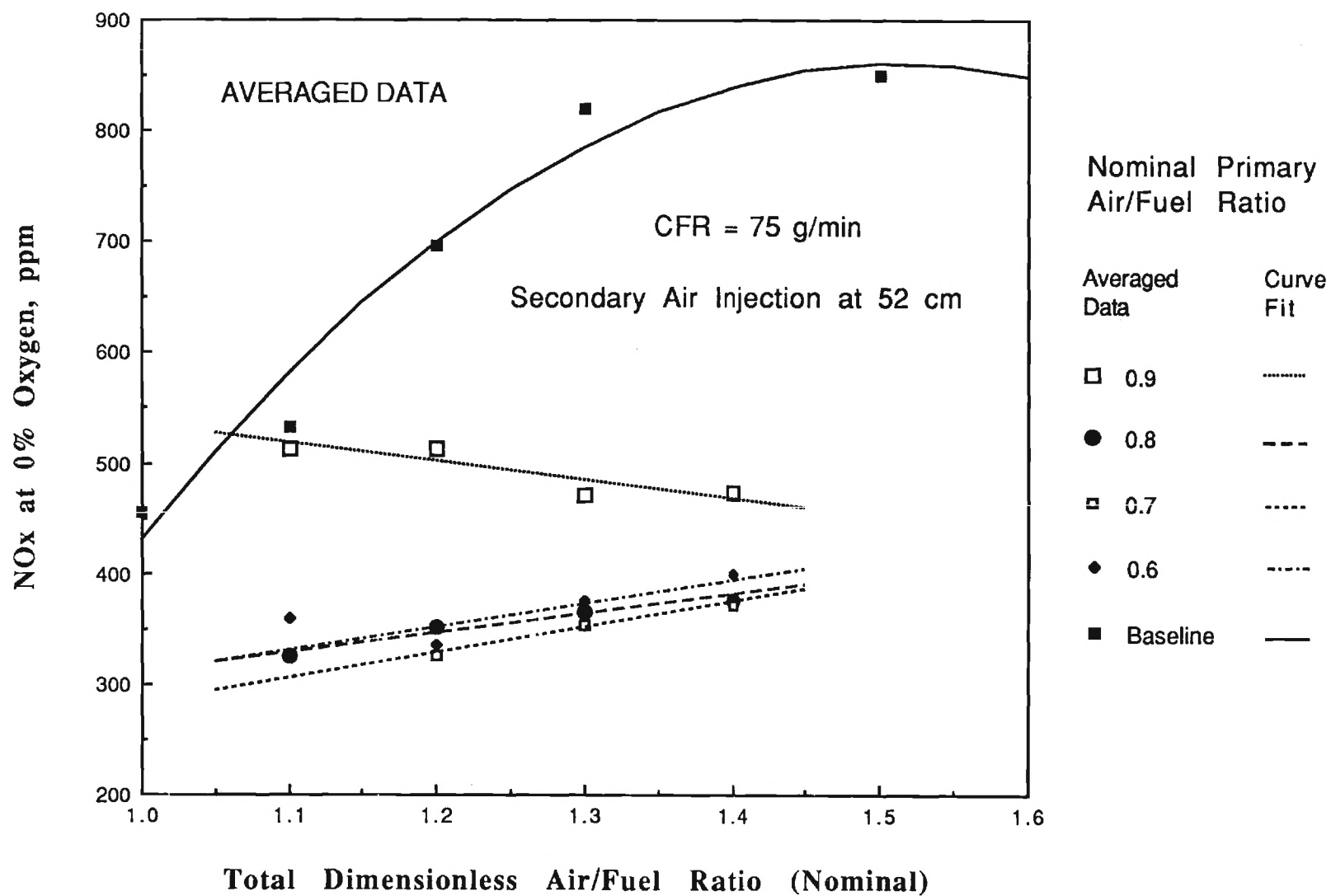


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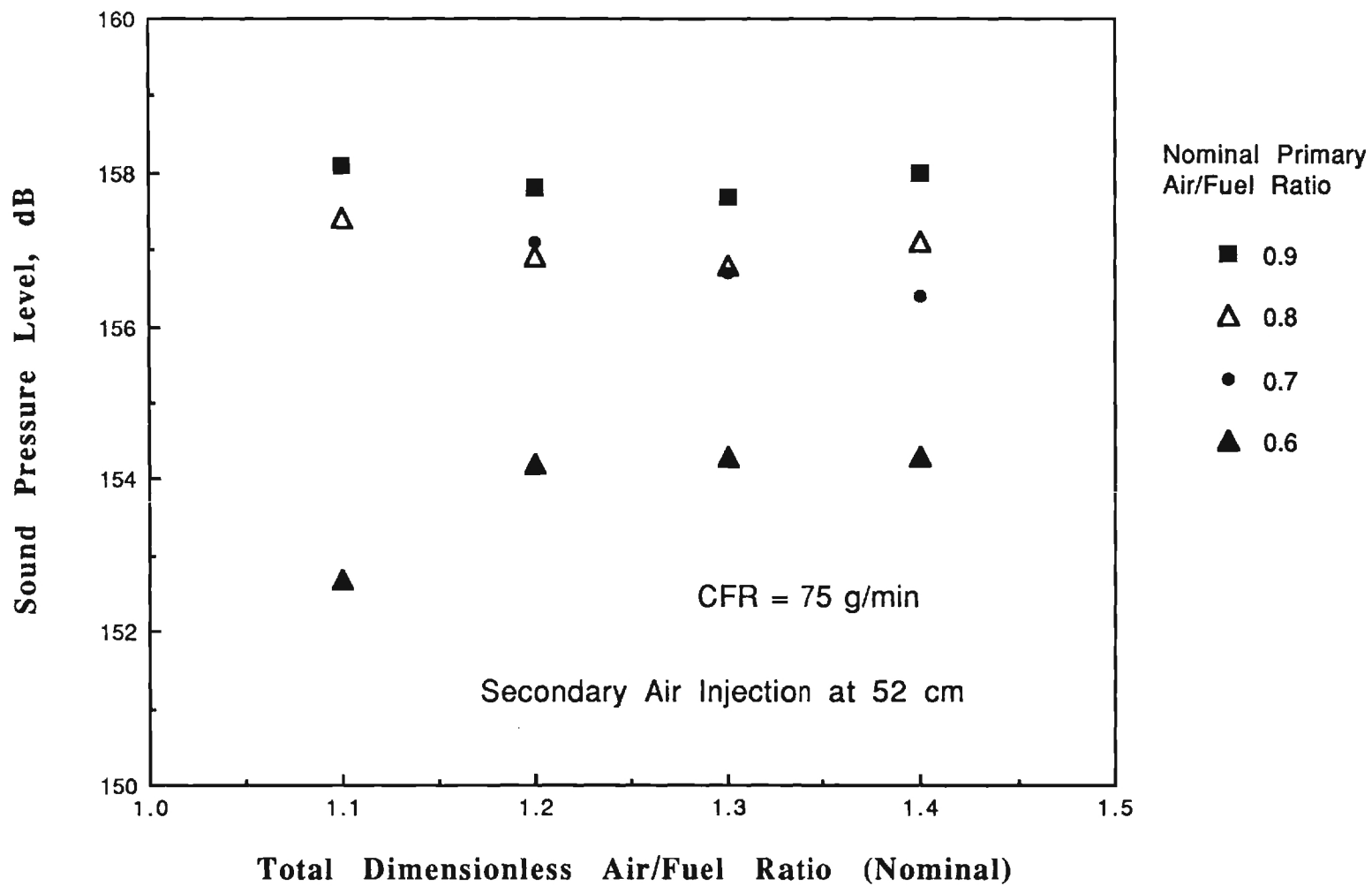


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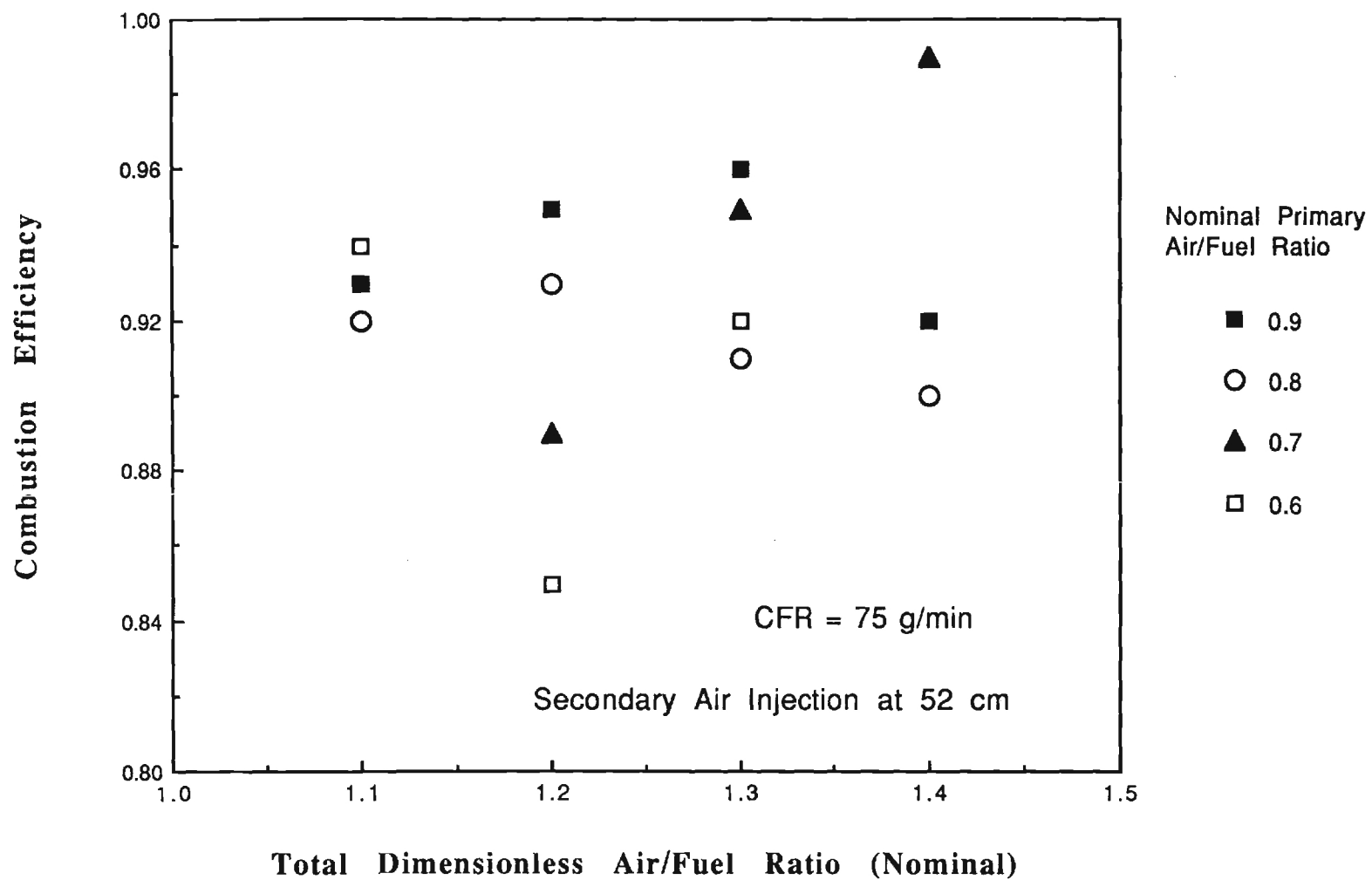


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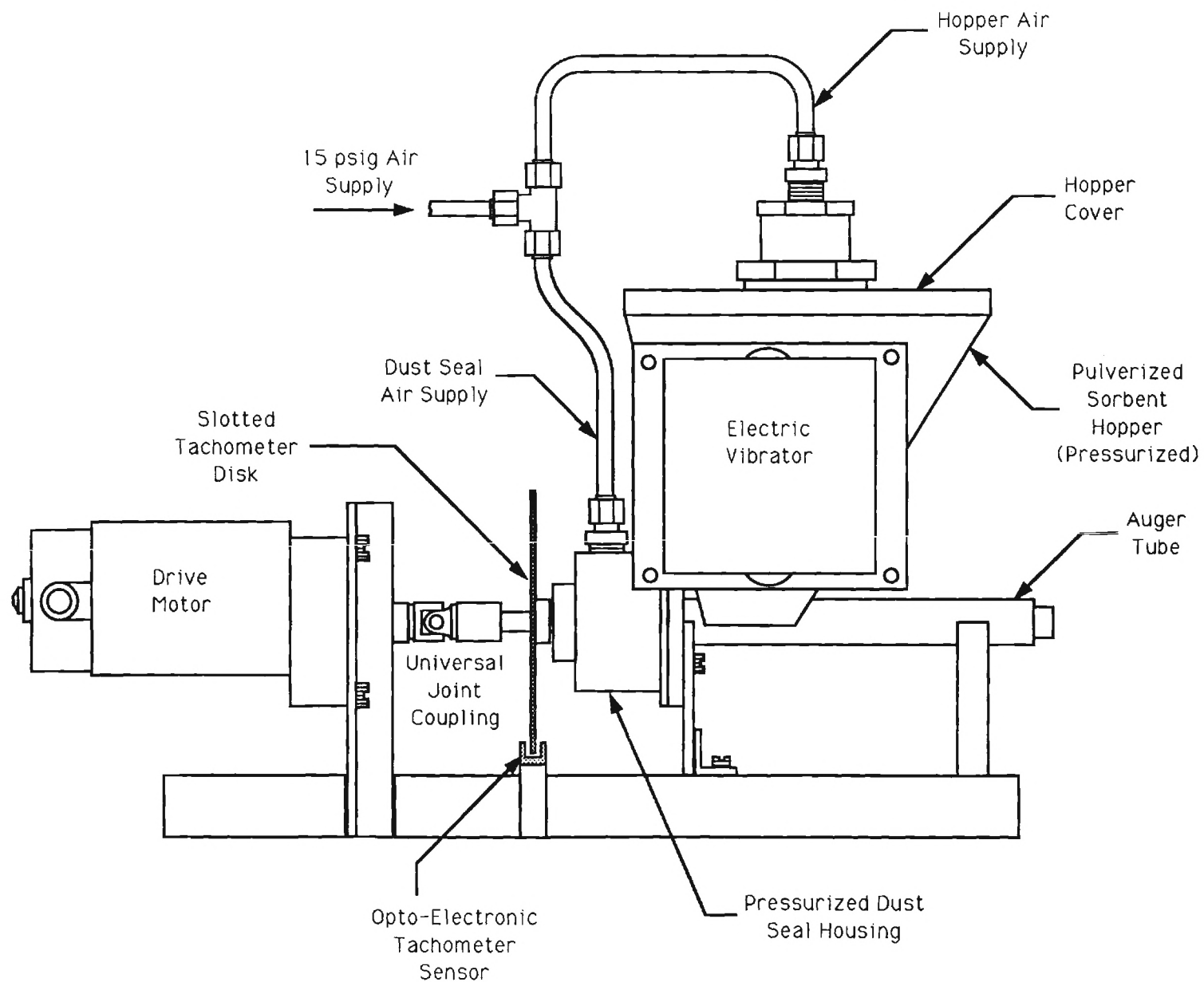


Figure 5. Modified Sorbent Feed System.

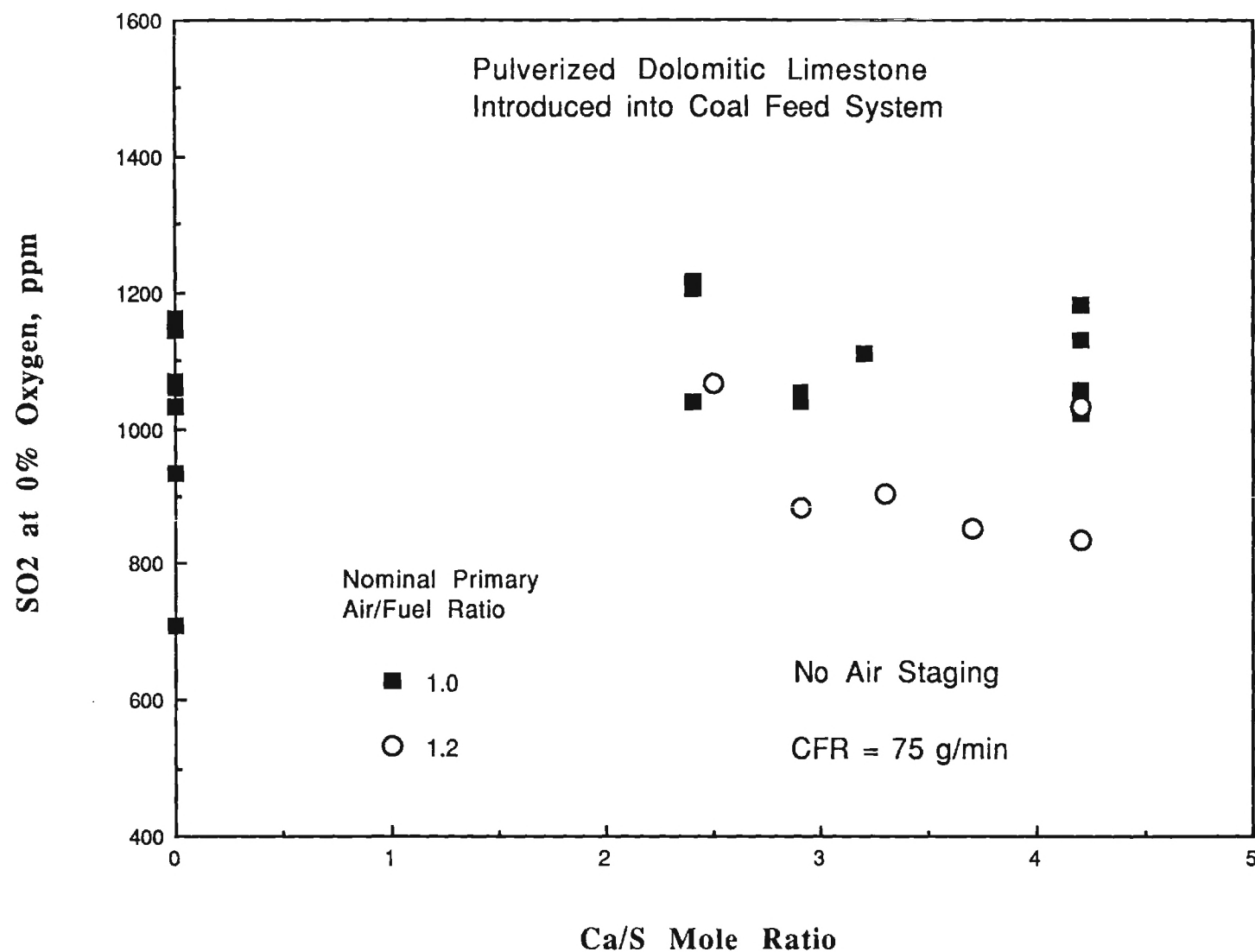


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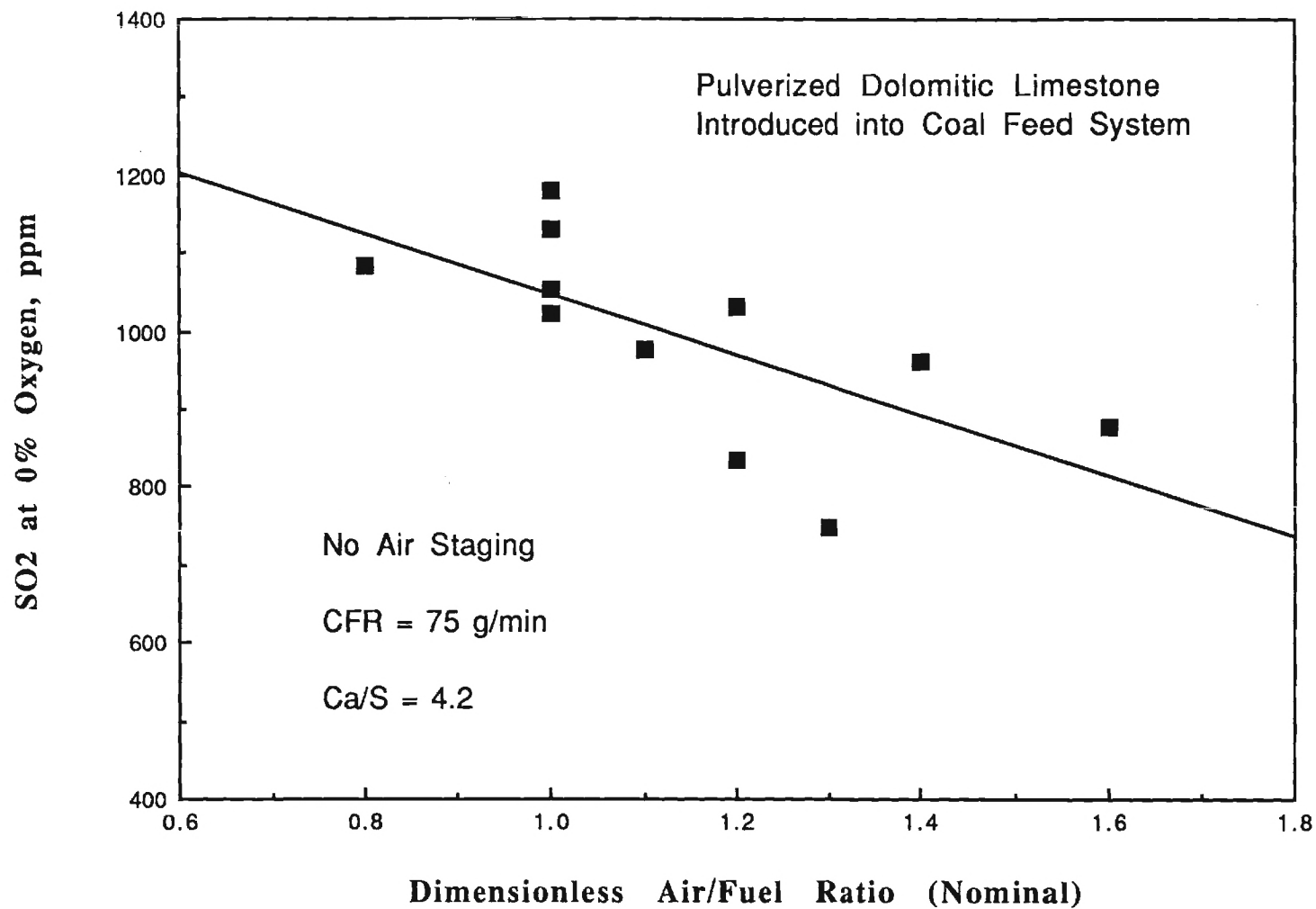


Figure 7. Effect of Primary Air/Fuel Ratio on Sulfur Dioxide Emissions for Tests with Addition of Pulverized Dolomitic Limestone Through the Coal Feed System.

**REDUCTION OF NO<sub>x</sub> AND SO<sub>2</sub> EMISSIONS  
FROM COAL BURNING PULSE COMBUSTORS**

**Final Report**

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Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy  
Office of Fossil Energy  
Pittsburgh Energy Technology Center  
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December, 1990

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## ABSTRACT

In this investigation, a Rijke pulse combustor was constructed, in which unpulverized coal was burned on a rotating bed where the presence of acoustic velocity oscillations resulted in bed fluidization and intensification of the combustion process. The objectives of this investigation were to determine (1) if the nitrogen oxides emissions of the experimental Rijke pulse combustor could be reduced by air staging the combustion process and (2) if the sulfur dioxide emissions of this pulse combustor could be reduced by the addition of sorbent materials such as limestone to the coal bed or to the gas stream above the bed.

A series of experiments was conducted without air staging or sorbent addition in order to determine the baseline emissions of  $\text{NO}_x$  and  $\text{SO}_2$ . A bituminous coal with about 1.5 percent nitrogen and about 1.3 percent sulfur was burned in all of the experiments. Under pulsating combustion conditions at a sound pressure level of about 160 dB and a frequency of about 65 Hz,  $\text{NO}_x$  emissions (3% oxygen basis) ranged from about 250 ppm for extremely fuel rich combustion ( $\alpha = 0.6$ ) to about 700 ppm for large excess air conditions ( $\alpha = 1.5$ ). Peak  $\text{SO}_2$  emissions of about 1400 ppm were measured at about 10 percent excess air, with minimum emissions of about 850 ppm for fuel rich combustion and somewhat less than peak emissions (about 1200 ppm) for large excess air conditions.

Air staging experiments were conducted for total dimensionless air fuel ratios ranging from 1.0 to 1.4 and primary dimensionless air/fuel ratios ranging from 0.6 to 0.9. Injection heights ranged from 20 cm to 52 cm above the coal bed. Air staging was effective in reducing the nitrogen oxides emissions of coal burning Rijke type pulse combustors under the proper conditions. The largest reductions in  $\text{NO}_x$  emissions were obtained for primary dimensionless air/fuel ratios of about 0.7 with sufficient secondary air injection to yield total dimensionless air/fuel ratios between 1.1 and 1.4. For excess air values less than about 10 percent, air staging resulted in only small reductions in  $\text{NO}_x$  emissions. The injection point for best  $\text{NO}_x$  reduction was about 50 cm above the bed. Under optimum conditions, reductions in  $\text{NO}_x$  emissions of up to 56 percent were obtained.

Another series of experiments was conducted using sorbent addition to reduce sulfur dioxide emissions. In some of these experiments, pulverized dolomitic limestone was introduced along with the coal through the coal delivery tube just above the bed, while in the remainder of the experiments, the sorbent was dispersed in an air stream and injected at 15 cm or 23 cm above the coal bed. For sorbent introduced into the coal feed stream, sulfur dioxide reductions of only about 20 percent were obtained for pulsating combustion with about 20 percent excess air. For these experiments, there was a definite trend of decreasing  $\text{SO}_2$  emissions with increases in excess air. Much higher  $\text{SO}_2$  reductions were obtained when the sorbent was injected using the air entrainment system. In one experiment, conducted at a Ca/S ratio of 2.4 with sorbent particles having a mean diameter of about 40  $\mu\text{m}$ , an  $\text{SO}_2$  reduction of 83 percent was obtained.

## INTRODUCTION

This final report summarizes the work accomplished under a research project entitled "Reduction of  $\text{NO}_x$  and  $\text{SO}_2$  Emissions from Coal Burning Pulse Combustors" which was supported under DOE Grant No. DE-FG-88PC88918 during the period September 1, 1988 through August 31, 1990.

This project is a continuation of earlier work done at Georgia Institute of Technology [1] which demonstrated that both bituminous and subbituminous coals can be burned with efficiencies greater than 97 percent in Rijke type pulse combustors with only 10 percent excess air. In a Rijke pulse combustor, unpulverized coal is burned on a bed where the presence of acoustic velocity oscillations results in bed fluidization and intensification in the rates of mass, momentum, and heat transfer processes; phenomena which are apparently responsible for the superior performance of the pulse combustor. However, further studies with this combustor [2] showed that the emissions of nitrogen oxides and sulfur dioxide exceeded allowable emission standards. This project was, therefore, concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

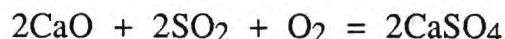
The first objective of this investigation was to determine if the nitrogen oxides emissions of an experimental Rijke pulse combustor could be reduced by air staging the combustion process. Most of the  $\text{NO}_x$  produced in coal combustors originates from the coal bound nitrogen, thus the control of this source of  $\text{NO}_x$  offers the greatest possibilities for  $\text{NO}_x$  reduction during coal combustion. Investigations of steady state coal burners have shown that staging the combustion process offers the greatest potential for  $\text{NO}_x$  reduction in coal combustors. In one form of combustion staging, known as air staging, the coal is burned in the first stage under fuel rich (gasification) conditions. In the absence of sufficient oxygen, the unstable nitrogen compounds released from the coal in the first stage ( $\text{HCN}$  and  $\text{NH}_3$ )

convert to harmless  $N_2$  rather than  $NO_x$ . The fuel gases generated in the first stage are burned in the second stage with the secondary air which is introduced into the combustor downstream of the first stage. To reduce thermal  $NO_x$  generation in the second stage, it is desirable to operate the second stage at low temperatures and with the minimum amount of secondary air which will result in acceptable performance and low  $NO_x$  formation. Reduction of  $NO_x$  production in steady state coal burners is discussed in detail in Refs. [3], [4] and [5]. Reduction of  $NO_x$  in coal burning pulse combustors by means of combustion staging has not been previously investigated.

The second objective of this investigation was to determine if the sulfur dioxide emissions could be reduced by adding sorbent materials such as limestone or dolomite to the acoustically fluidized bed or to the flow of combustion gases above the bed. It is well known that combustion of a high sulfur coal in a fluidized bed of sorbent particles reduces  $SO_2$  emissions. Naturally occurring limestone ( $CaCO_3$ ) and dolomite ( $CaCO_3:MgCO_3$ ) have been found to be good sorbents, with the former being better suited for atmospheric pressure fluidized beds and the latter more suited to pressurized fluidized beds. In atmospheric pressure fluidized beds, the limestone is first calcined in the endothermic reaction:



which readily occurs at temperatures well below the bed temperature. The calcined limestone then reacts with the sulfur dioxide in the following reaction:



The calcination step has been found to result in a porous sorbent particle structure, which creates a large internal surface area which increases the rate of sulfation. The reaction product  $CaSO_4$ , obtained in the sulfation reaction, is bulkier than the reactant  $CaO$ , and it tends to choke the porous structure inhibiting further sulfation.

Consequently, the sorbent utilization is limited, thereby requiring excessively large quantities of sorbents to achieve compliance with national emission standards. Extensive studies at Argonne National Laboratory in the U. S. [6] and at CRE and BCURA in the U. K. [7] have examined in considerable detail the effect of various operating parameters and variables on the sulfation process.

The following work will be described in this report: (1) design, fabrication and assembly of the Rijke tube pulse combustor and the auxiliary systems, (2) baseline experiments to determine the  $\text{NO}_x$  and  $\text{SO}_2$  emissions in the absence of sorbent addition or combustion staging, (3) air staging experiments to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the  $\text{NO}_x$  emissions, (4) non-pulsating experiments to determine the effect of pulsations on the  $\text{NO}_x$  emissions, and (5) sorbent addition experiments to determine the effectiveness of limestone or dolomite addition in reducing the  $\text{SO}_2$  emissions. Finally a summary of the experimental results obtained under this project and the major conclusions will be given.

## EXPERIMENTAL APPARATUS

### RIJKE TUBE COAL COMBUSTOR

The Rijke pulse combustor basically consists of a vertical steel tube which is open at the upper end and connected to an acoustic decoupler at the lower end. The coal bed is located one quarter of the distance from the upstream (lower) end of the tube to the downstream (upper) end. The combustion process interacting with the mean flow through the tube excites the fundamental acoustic mode for an open-ended tube. For this mode the pressure oscillations are a maximum at the middle of the tube, while the acoustic velocity oscillations are a maximum at the ends of the tube. The open-ended boundary condition requires the pressure perturbations to be zero at the ends of the tube. The acoustic decoupler at the lower end is a section of pipe with a much greater cross-sectional area than the

Rijke tube itself. This preserves the open-ended boundary condition, while allowing control of the air flow through the combustor. The basic Rijke tube geometry along with the fundamental mode pressure and velocity profiles are shown in Figure 1.

The Rijke tube coal combustor was designed to allow operation at two different pulsation frequencies by changing the length of the tube, while maintaining the combustion at the quarter-length point. This was accomplished by means of a vertical insulated pipe section 183 cm long, which contains the coal bed, to which various horizontal pipe sections can be added. The two configurations are shown in Figure 2. In the short configuration, which has a total length of 3.05 m, a vertical section of uninsulated pipe is connected to the top of the insulated section. The bottom of the insulated section is connected to the decoupler by means of an elbow and a short horizontal pipe section. In the long configuration, which has a total length of 6.10 m, two additional lengths of horizontal pipe are added. At the bottom (decoupler) end of the system, a 76-cm pipe section is inserted between the elbow and the short pipe section connected to the decoupler. At the top (exhaust) end, the vertical pipe is replaced by an elbow and a 1.93 m horizontal section of pipe leading to the exhaust. In both configurations, the coal bed is located 12.7 cm above the lower end of the vertical insulated pipe section.

The Rijke tube pulse combustor in the short configuration is shown in more detail in Figure 3 along with the primary and secondary air supplies, the coal feed system, and the sorbent feed system. The vertical insulated combustion section of the Rijke tube is made from 25.4 cm I. D. carbon steel pipe lined with 5 cm thickness of a castable ceramic insulation (Babcock and Wilcox Kaocrete HDHS 98 RFT) leaving a central bore diameter of 15 cm. This section is provided with three quartz viewing windows and is instrumented with several chromel-alumel (Type K) thermocouples and a piezoelectric pressure transducer at the middle of the combustor. A gas sampling port is located in the exhaust section attached to the upper end of the combustion section. Coal is fed continuously into the

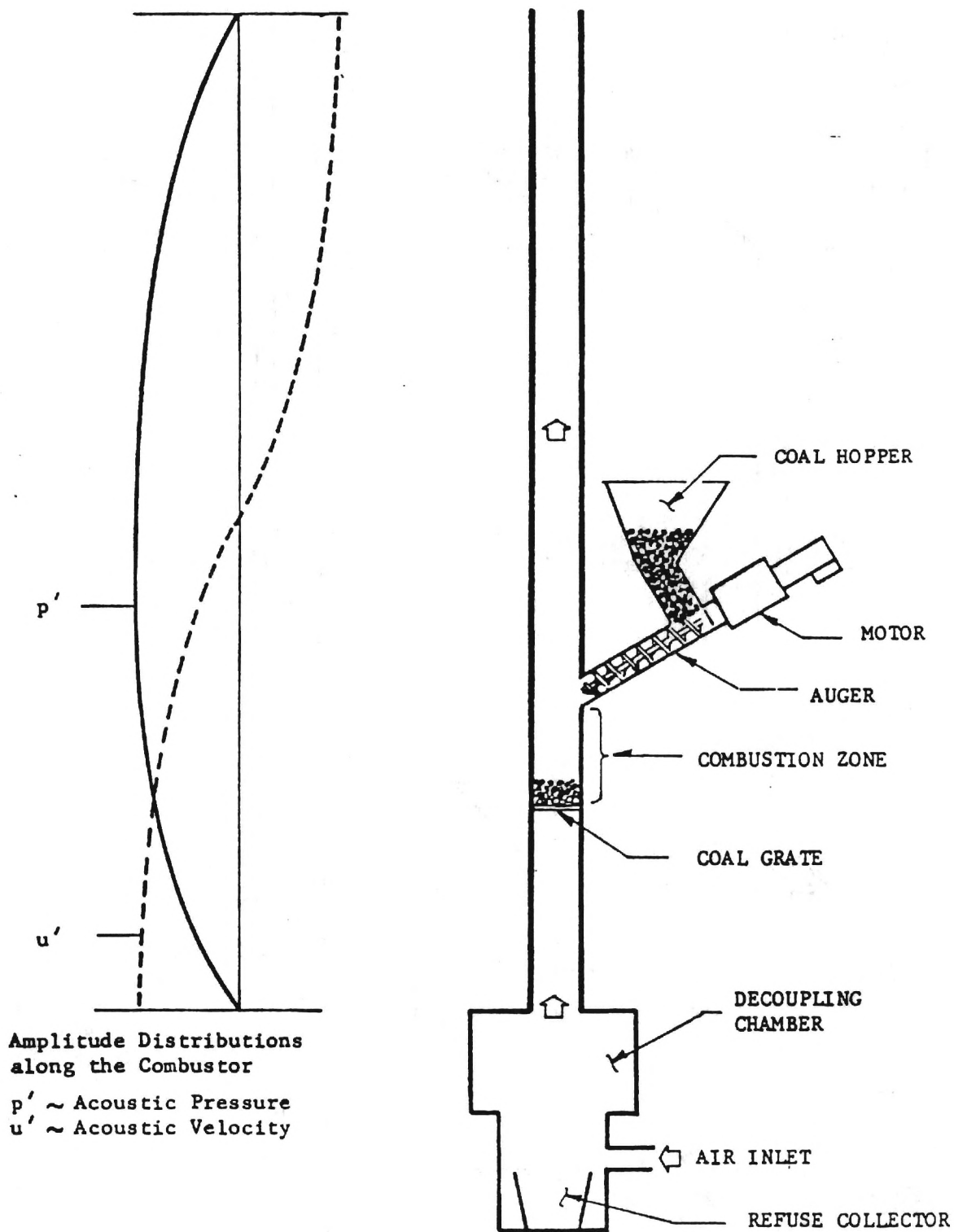


Figure 1. A Schematic of the Coal Burning Rijke Tube Pulsating Combustor Developed at Georgia Tech and Its Acoustic Wave Structure.

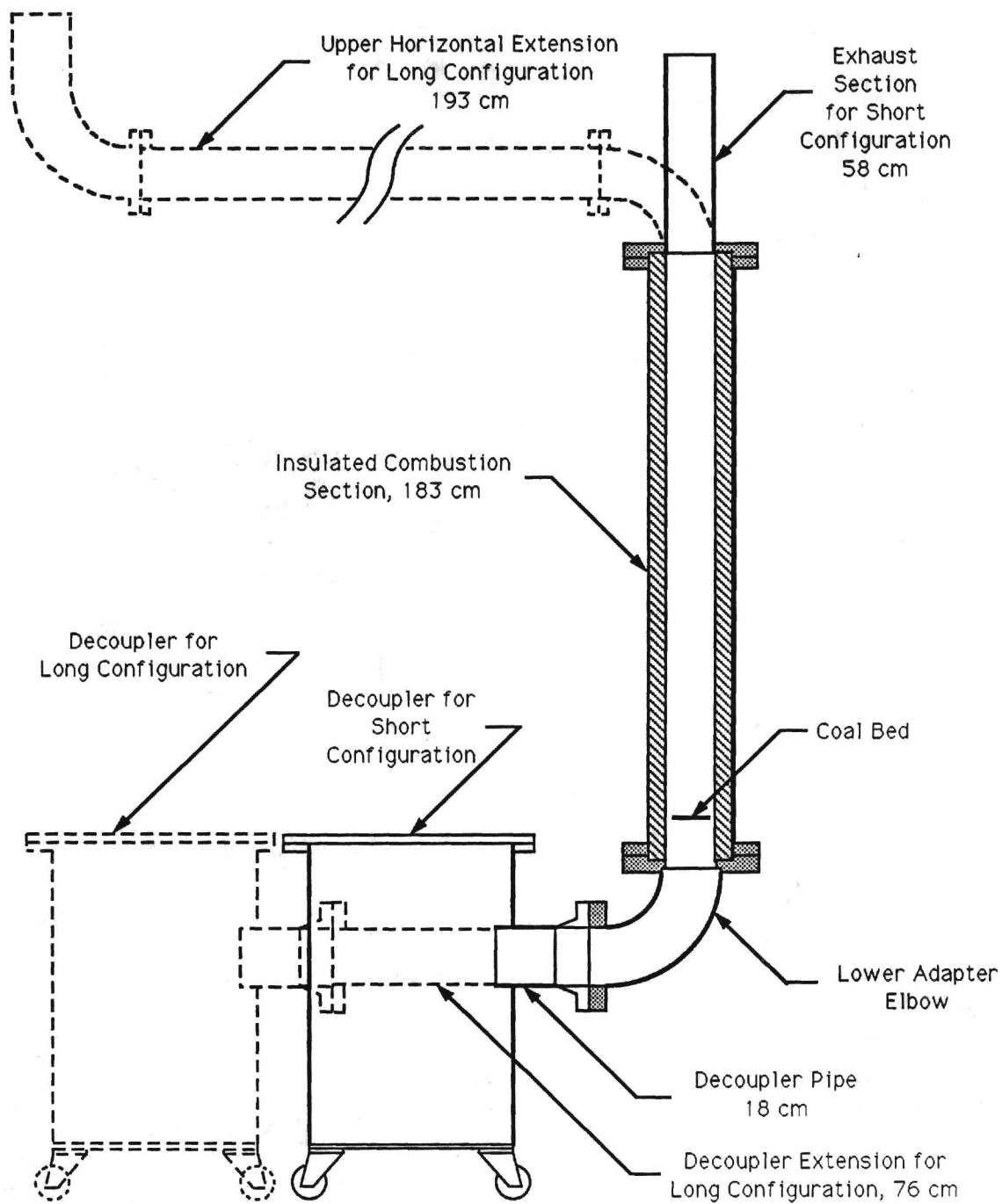


Figure 2. Rijke Pulse Combustor Configurations

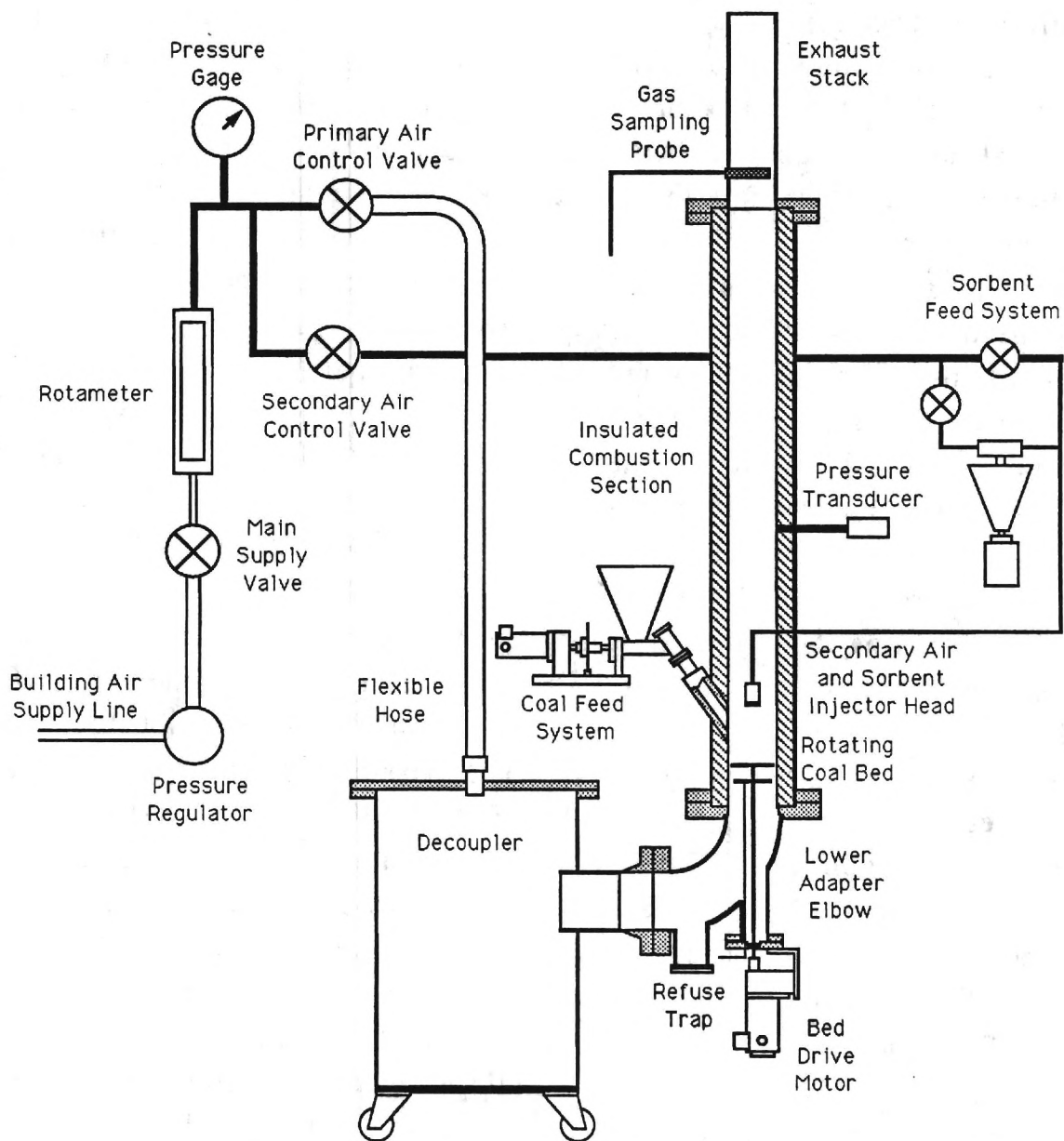


Figure 3. Rijke Pulse Combustor and Auxiliary Systems

combustion tube by a motor driven auger supplied by a hopper. The coal is supported by a motor driven rotating bed, which gives uniform distribution of coal on the bed. Bed rotation also grinds the ash particles down to sufficiently small sizes that they can continuously fall through the bed grid, thus preventing accumulation of coal and ash on the bed. During combustor operation, ash and unburned coal which fall through the bed accumulate in a refuse trap at the bottom of the lower adapter elbow which can be emptied periodically. The primary combustion air enters the combustor from the decoupler and passes vertically through the coal bed. The coal is ignited by a propane burner located just below the bed. For combustion staging experiments, a secondary air system delivers air through a radial injector located at the axis of the combustor above the bed. The injector height above the bed can be varied.

The rotating bed assembly is shown in Figure 4. The support for the rotating bed grid is a spoked wheel fabricated from carbon steel which fits closely within a stationary ring of the same material. The ring is attached to the refractory lining of the combustor and provides a seal preventing air from bypassing the bed around its periphery. The bed grid is made of #6 mesh stainless steel grid which will retain coal particles larger than about 3 mm in diameter. The bed grid is spot welded to the rotating support wheel. The support wheel is connected by two screws to a 65 cm long 1.2 cm diameter shaft which passes through two ball bearings at the lower end. The bearings are supported by a bearing house flange which is attached to the flanged pipe extending downward from the lower adapter elbow. The rotating bed is driven by a variable-speed DC geared motor.

A detailed view of one of the observation windows is shown in Figure 5. The three quartz windows measure 30.5 cm long by 6.4 cm wide by 1.9 cm thick. These are located at the bed level, the center, and the upper end of the combustion section. About a third of the length of the bed level window extends below the bed to allow viewing the ignition/preheating system and the underside of the bed

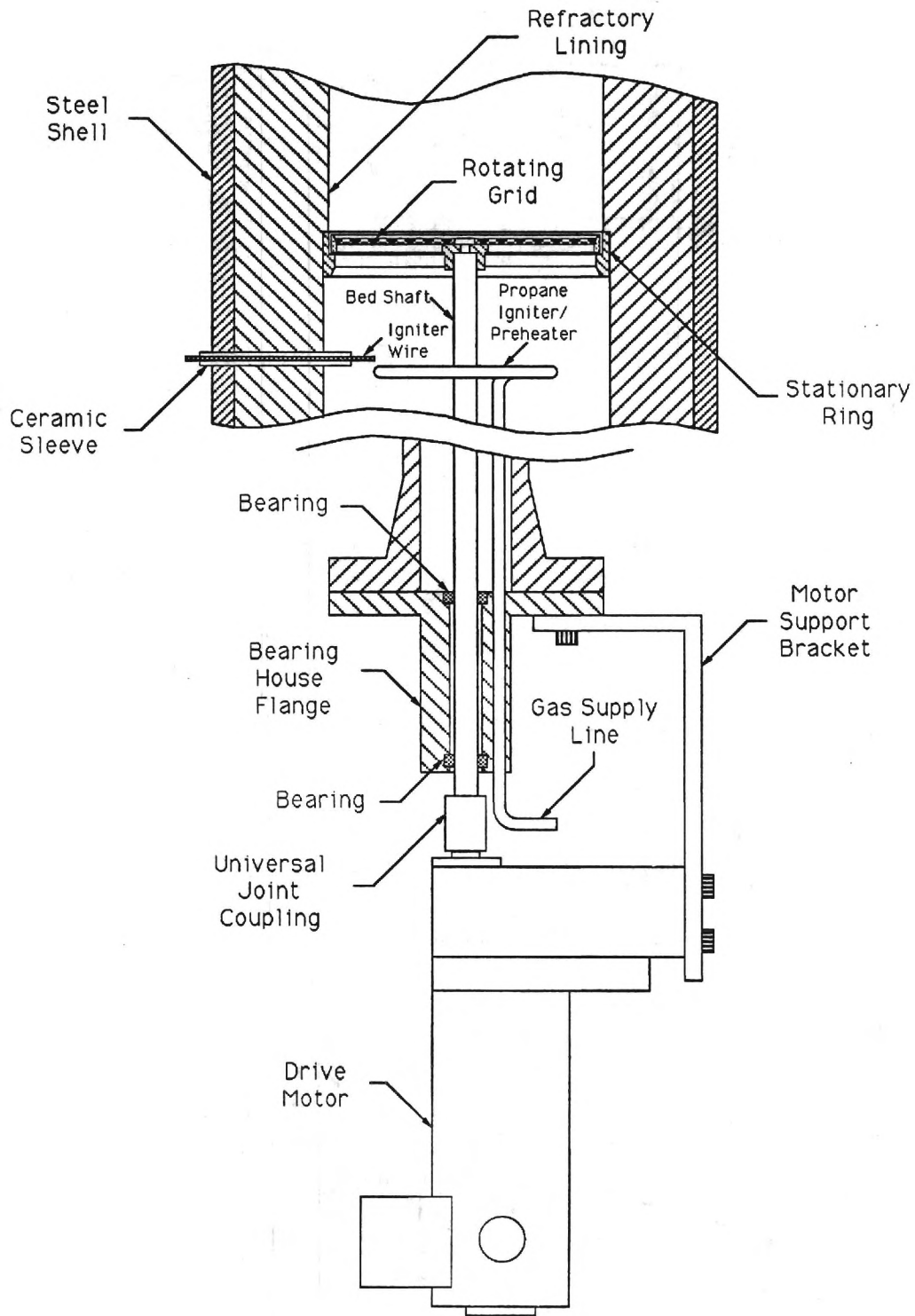


Figure 4. Rotating Bed Assembly.

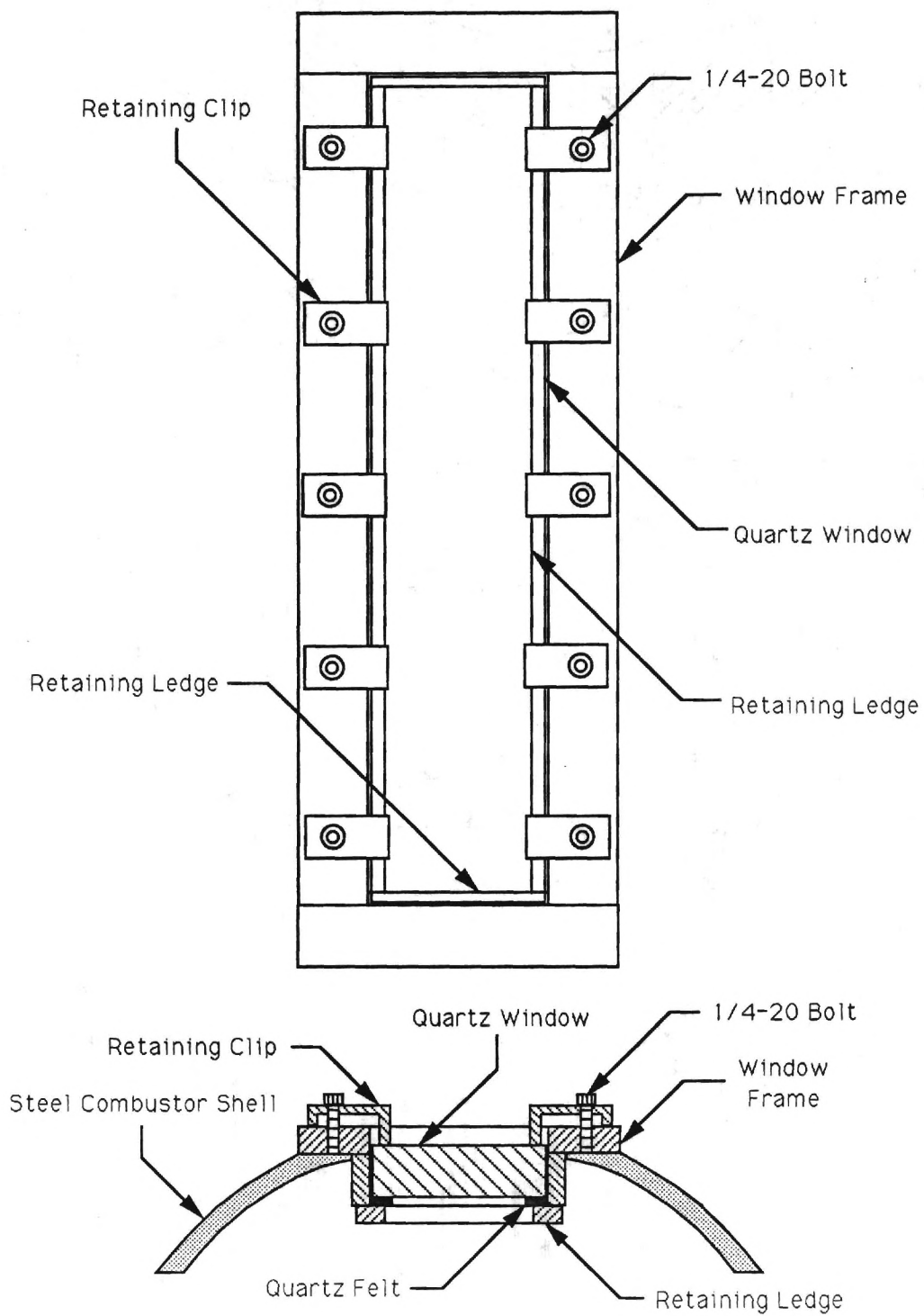


Figure 5. Combustor Observation Window

during combustor operation. Each window is seated in a stainless steel frame which was welded into a hole cut in the steel combustor shell. Quartz felt strips were installed around the perimeter of each window frame and cemented in place using a high temperature RTV compound. These provide a buffer between the quartz window and the steel window frame and serve as a seal against gas leaks. Each window is held in place using ten bolt-mounted clips. The bed level window required special provisions to close the gap between the forward edge of the coal bed and the inner surface of the quartz window. This was necessary to prevent air from bypassing the bed and to prevent coal and ash particles from falling through this gap. A removable ceramic block mounted on a horizontal stainless steel plate was fabricated to fit in the gap between the bed and the window. This block is supported by two notches in the vertical edges of the window frame.

## AIR SUPPLY SYSTEM

The air supply system is shown in Figure 3. This system supplies the main combustion air and also auxiliary air for either the sorbent injection system or the secondary combustion air. Air from the 850 kPa building air supply passes through a pressure regulator set at 340 kPa to a 3.8 cm diameter flexible hose (rated at 1030 kPa) which is connected to a control valve on the control panel. The flowrate into the combustor is controlled and monitored by means of a rotameter. The air pressure is measured just downstream of the rotameter. The line from the rotameter is split into primary and secondary lines, each with a control valve. The primary line is connected to the decoupler by a 3.8 cm diameter flexible hose. The secondary air passes through 0.95 cm diameter copper tubing to a port in the combustor wall located a short distance above the desired secondary air injection point. A sidebranch in the secondary air line contains the sorbent feed and entrainment system. Within the combustion section, a length of 0.95 cm diameter stainless steel tubing leads downward from the port in the combustor wall to the injector head on the combustor axis. The injector head, which is used

for both secondary air injection and sorbent injection, is described in detail in the discussion of the sorbent feed system.

## IGNITION/PREHEATING SYSTEM

The ignition/preheating system is shown in Figures 4 and 6. Propane from a supply tank flows through 1.27 cm diameter copper tubing to a shut-off valve on the control panel (Figure 6). This is followed by a solenoid valve, a control valve, and a rotameter. The solenoid valve is controlled by an ultraviolet flame detector mounted outside the lower combustor window. The solenoid valve automatically shuts off the flow of propane to the combustor if the flame detector does not sense a flame in the combustor. An "override" system allows the solenoid valve to be opened, independently of the flame detector, to permit igniting the burner. The control valve is used to adjust the propane flow rate as measured by the rotameter. The propane then flows through a 0.64 cm diameter copper line which is connected to the stainless steel burner ring located below the coal bed (Figure 4). The burner ring is shown in detail in Figure 7. The propane burns as a diffusion flame in the air stream supplied to the combustor. The air/fuel ratio is controlled by adjusting the air and propane flow rates to the combustor. The gas is ignited by a spark ignition system using a 10 kV AC power supply. The switches controlling the spark ignition system are located on the main control panel.

## COAL FEED SYSTEM

The coal feed system is shown in Figure 8. A horizontal auger 18 cm long and 3.8 cm in diameter delivers the coal from a hopper into an inclined water-cooled coal delivery tube leading into the combustor above the bed. The variable speed drive motor is coupled to the auger shaft by a universal joint in order to prevent problems due to any slight misalignment of the motor shaft and the auger shaft. The rectangular base of the hopper was welded directly to the auger tube with its long axis parallel to the axis of the auger. To

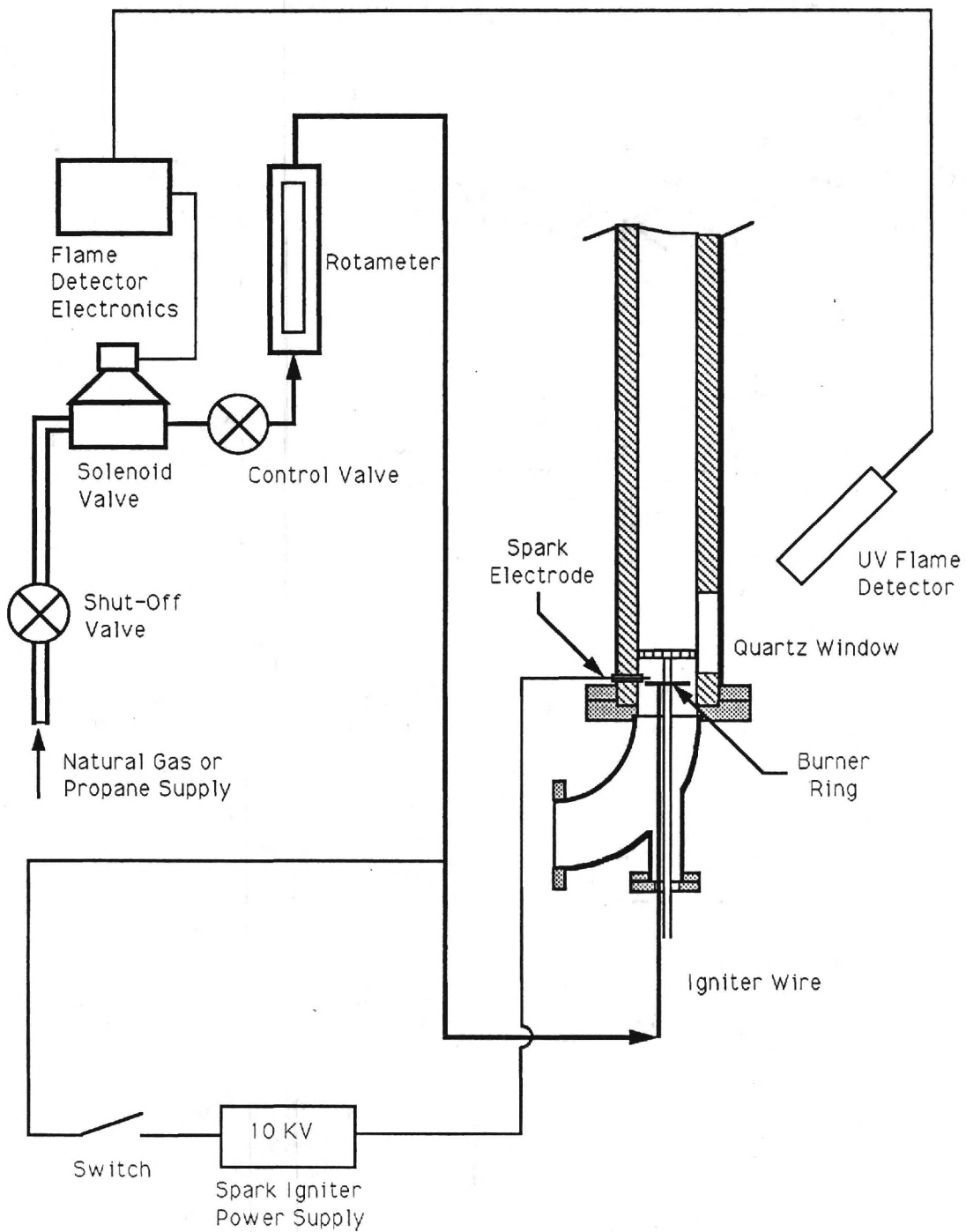


Figure 6. Rijke Combustor Ignition/Preheating System

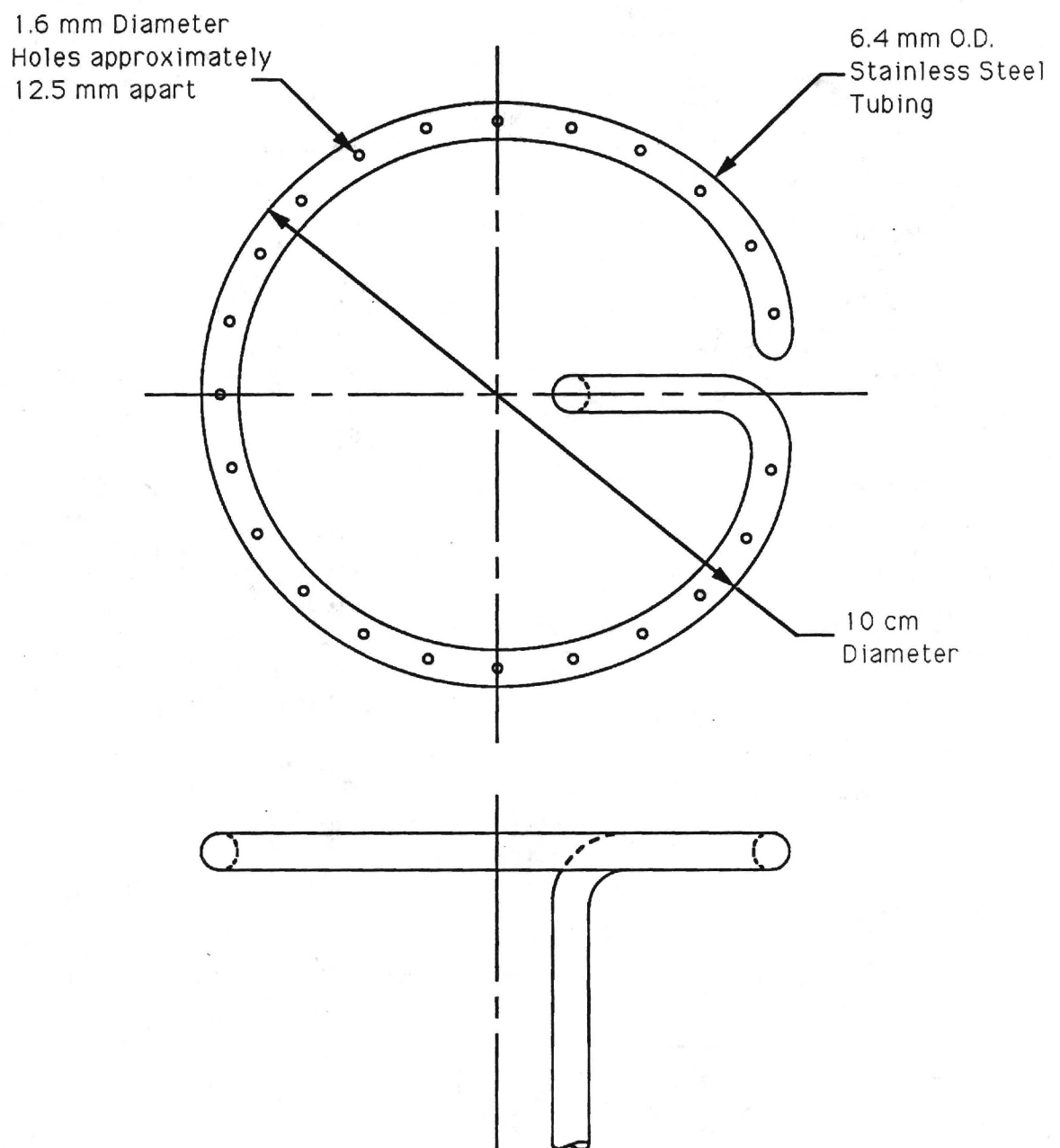


Figure 7. Igniter - Preheater Ring

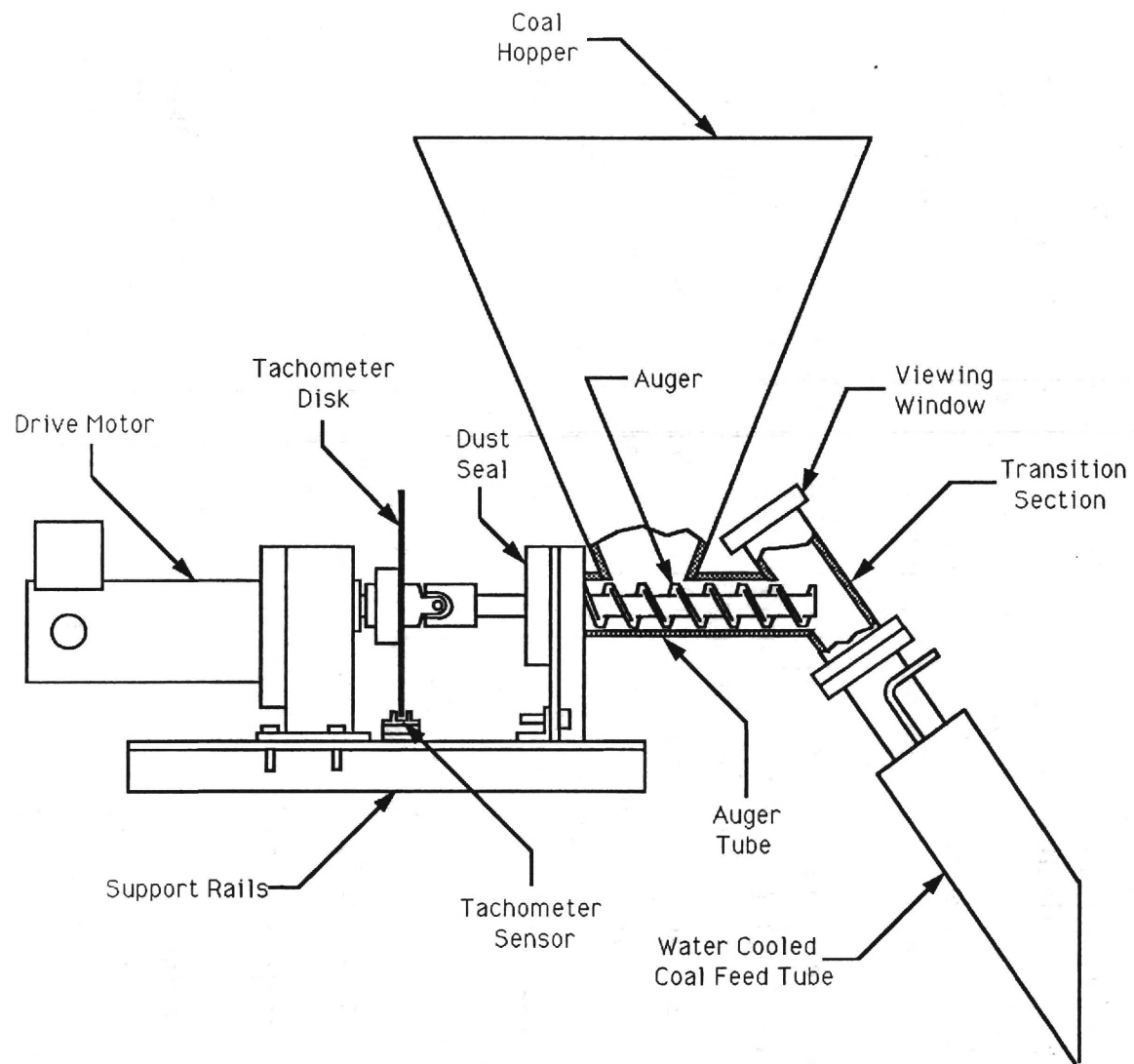


Figure 8. Horizontal Coal Feed Auger.

facilitate disassembly, the auger tube was welded to a short flanged section of pipe which was then bolted to the coal delivery tube.

An opto-electronic tachometer was installed on the coal feed system in order to obtain instantaneous auger speed (RPM) measurements needed to determine the coal feed rate. A slotted disk was attached to the auger shaft such that it passes between a LED light source and a photodiode as shown in Figure 9. As the wheel rotates, it periodically interrupts the light beam giving a pulsed output which is read by a frequency meter. The disk has 60 slots, thus the frequency reading in Hz yields the auger speed directly in RPM. The maximum speed of the coal feed auger is about 20 RPM.

The inner pipe of the inclined coal delivery tube is the same diameter as the auger tube (4.25 cm I.D.), and the outer pipe forming the water jacket has an inside diameter of 6.32 cm. Water enters the cooling jacket through a 6.4 mm O.D. stainless steel tube extending nearly to the lowest (and hottest) end of the annular water cavity and exits through another stainless steel tube near the top on the opposite side. The water cooling is needed primarily to prevent the coal from sticking to the inside of the delivery tube and eventually blocking the tube. The coal delivery tube was also provided with a viewing window at its upper end to facilitate the determination of the cause of any failure of the auger to feed properly.

## SORBENT FEED SYSTEM

The sorbent feed assembly consists of a drive motor, hopper and auger mounted on rails as shown in Figure 10, a sorbent entrainment venturi shown in Figure 11, and a sorbent injection nozzle shown in Figure 12.

In earlier sorbent feed system designs, two difficulties were encountered. First, after filling the hopper with limestone, the auger would feed for only about a minute before a cavity formed in the limestone around the entrance to the auger. This phenomenon,

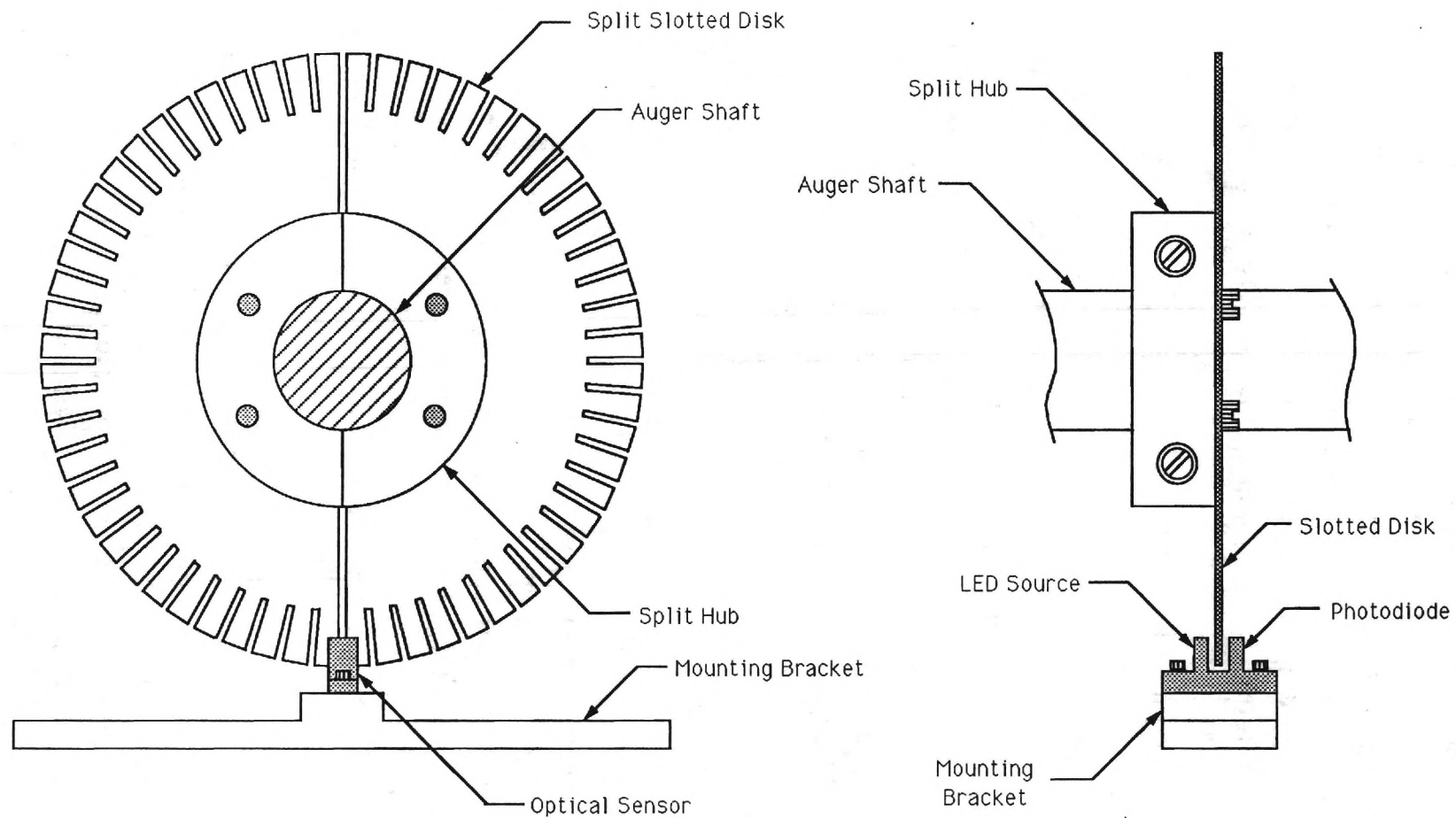


Figure 9. Opto-electronic Tachometer for Coal Feed Auger.

referred to as "bridging" or "rat-holing", is commonly encountered when attempting to transport finely pulverized materials. The second problem was that at the required air flow rates the pressure at the venturi throat was greater than atmospheric, resulting in air "blowback" through the auger and out through the hopper. Of course during blowback conditions, it was impossible to feed limestone into the venturi.

In order to overcome the "bridging" problem, the vertical auger configuration originally used was abandoned in favor of the horizontal auger configuration shown in Figure 10. Thus gravity would be more effective in maintaining flow to the auger and preventing bridging. However, tests with the horizontal auger revealed that bridging was still a serious problem. Since it is well known that mechanical vibration of similar feed systems may alleviate "bridging", a motor driven vibrator was mounted on one side of the sorbent hopper. The feed system was itself mounted on a separate stand so it is free to vibrate and to eliminate transmission of vibrations to the combustor and other components. This arrangement was found to successfully eliminate "bridging" and allow feeding of the pulverized sorbent material at a uniform rate.

The sorbent entrainment "venturi" shown in Figure 11 serves principally as a transition from circular cross-section tubing to a rectangular cross-section entrainment section and back to circular tubing again. The rectangular cross-section was needed in order to give a flush fit with the exit end of the auger. After encountering the blowback problem, it was discovered that the venturi throat area was too large, resulting in a throat pressure nearly equal to the pressure at the exit of the venturi, which was greater than atmospheric pressure due to downstream friction losses. (The pressure at the limestone injector orifice must be atmospheric for subsonic flow.) Thus the venturi was designed to have a variable throat area. To prevent the possibility of clogging, the minimum allowable throat height is about 0.8 mm with a width of 12.7 mm. Tests indicated that reducing the throat area reduced the throat pressure to below atmospheric pressure in the absence of sorbent

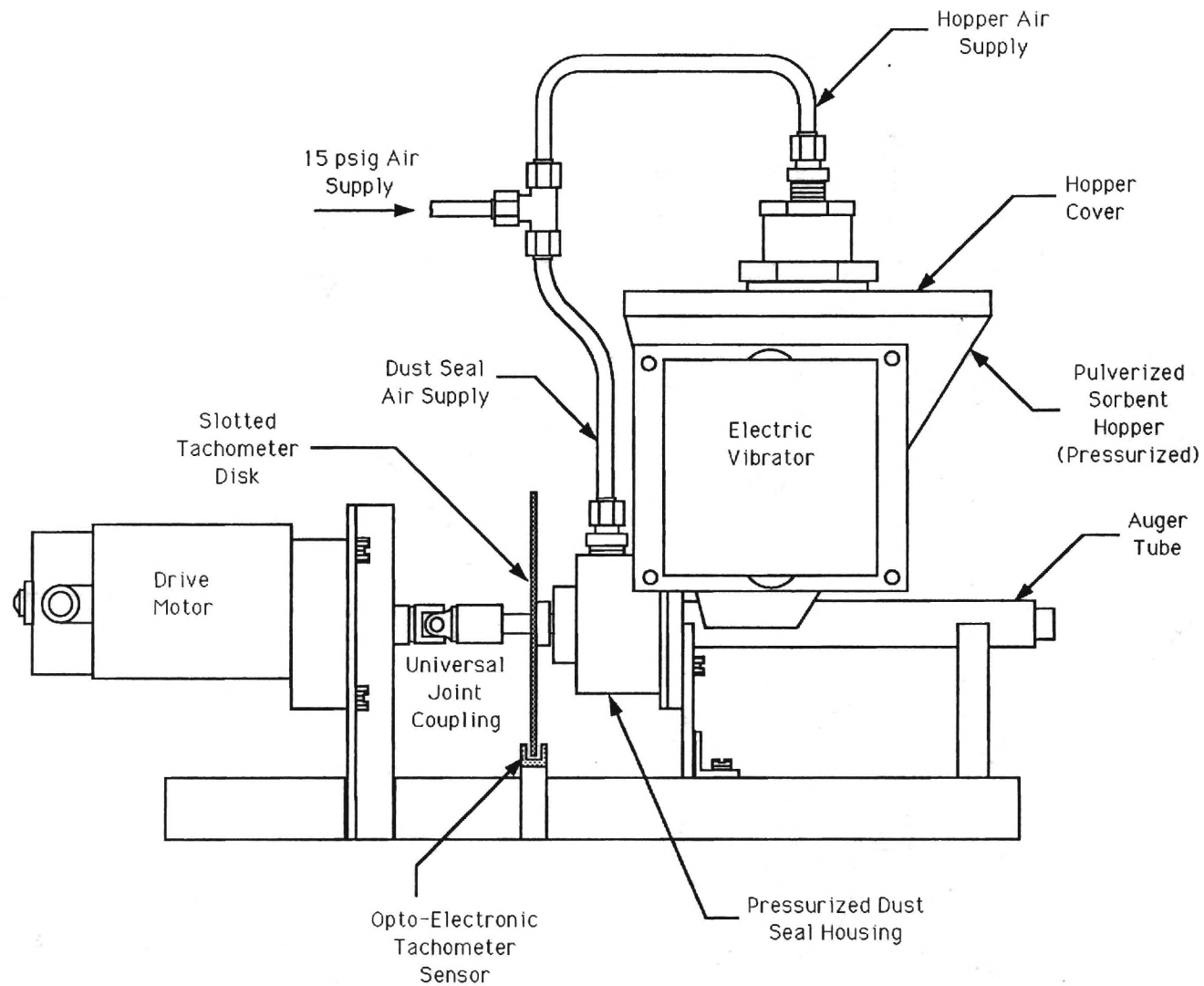


Figure 10. Modified Sorbent Feed System.

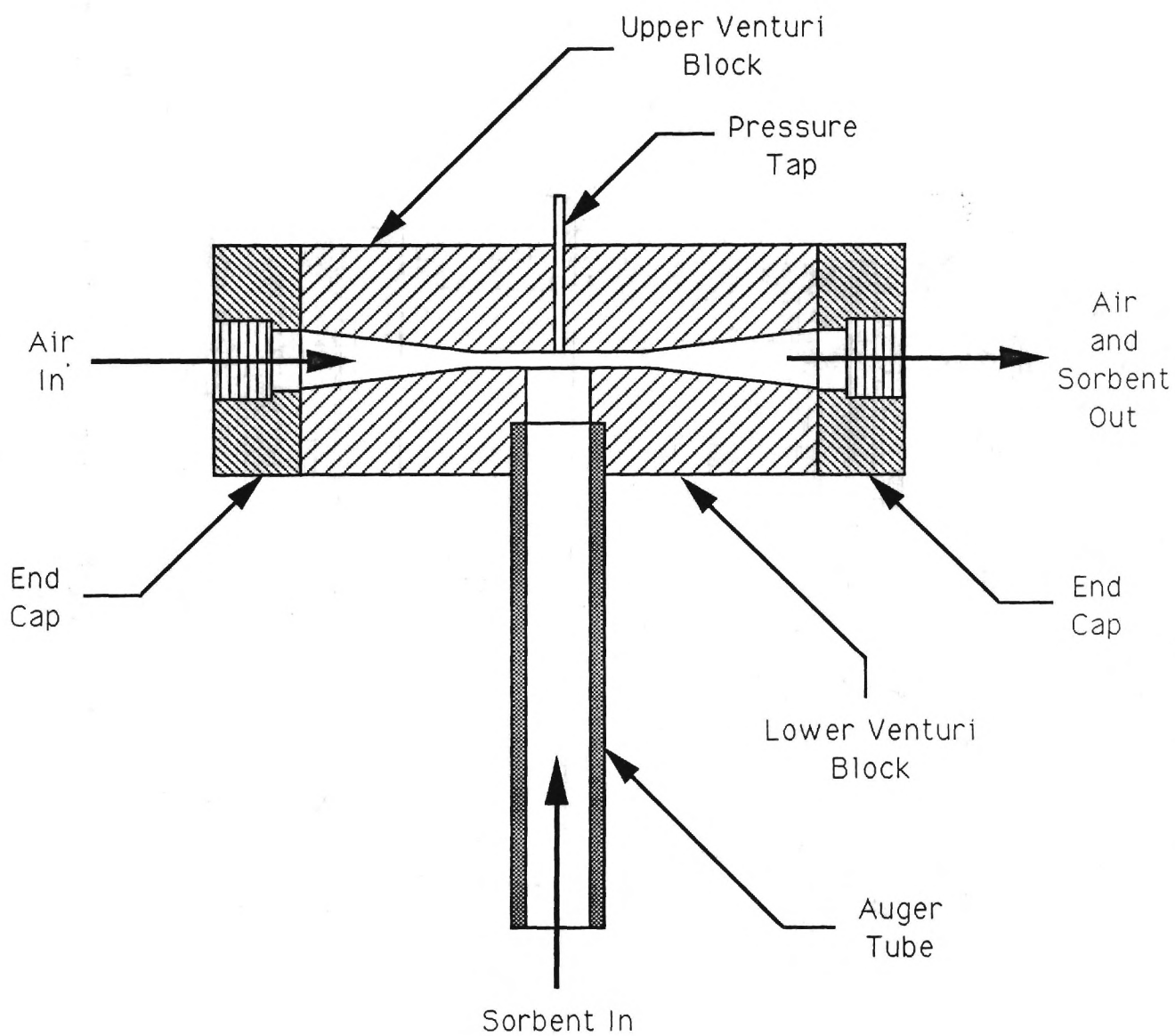


Figure 11. Pulverized Sorbent Entrainment Venturi.

material, but the throat pressure became greater than atmospheric pressure when sorbent was introduced into the venturi. This increased pressure, which again resulted in blowback through the auger and hopper, was due to the increased downstream resistance caused by the presence of the sorbent particles. To prevent blowback the hopper was modified so that it could be pressurized (Figure 10). A steel cover plate was welded to the top of the hopper. A threaded pipe connection allows filling of the hopper with pulverized sorbent, after which an air supply line is connected. A dust seal bearing at the base of the auger prevents dust blowback into the laboratory when the hopper is pressurized. Subsequent tests revealed that the blowback problem was successfully eliminated.

A tachometer system was also installed on the sorbent feed auger shaft to determine the instantaneous rotational speed of the auger which is needed in order to accurately measure the sorbent feed rate into the combustor. This tachometer is similar to the one installed on the coal feed system (Figure 10). A bracket mounted on the support rails holds an opto-electronic sensor whose signal is sent to the same electronic pulse counter used for the coal feed system.

A detail of the sorbent injector head is shown in Figure 12. The injector head consists of a conical nozzle section with a conical centerbody. This directs the axial flow in the delivery tube radially outwards into the combustion gases. The exit gap can be adjusted in order to obtain the optimum injection velocity for dispersing the sorbent particles over the cross-section of the Rijke tube.

## INSTRUMENTATION

Eight thermocouples were installed to measure gas temperatures on the axis of the combustor at several distances above the coal bed. All thermocouples used were Type K (chromel-alumel) with 1.6 mm diameter Inconel sheaths. The thermocouples were connected to a multichannel sequential switching device which was connected to a digital temperature readout. The thermocouple

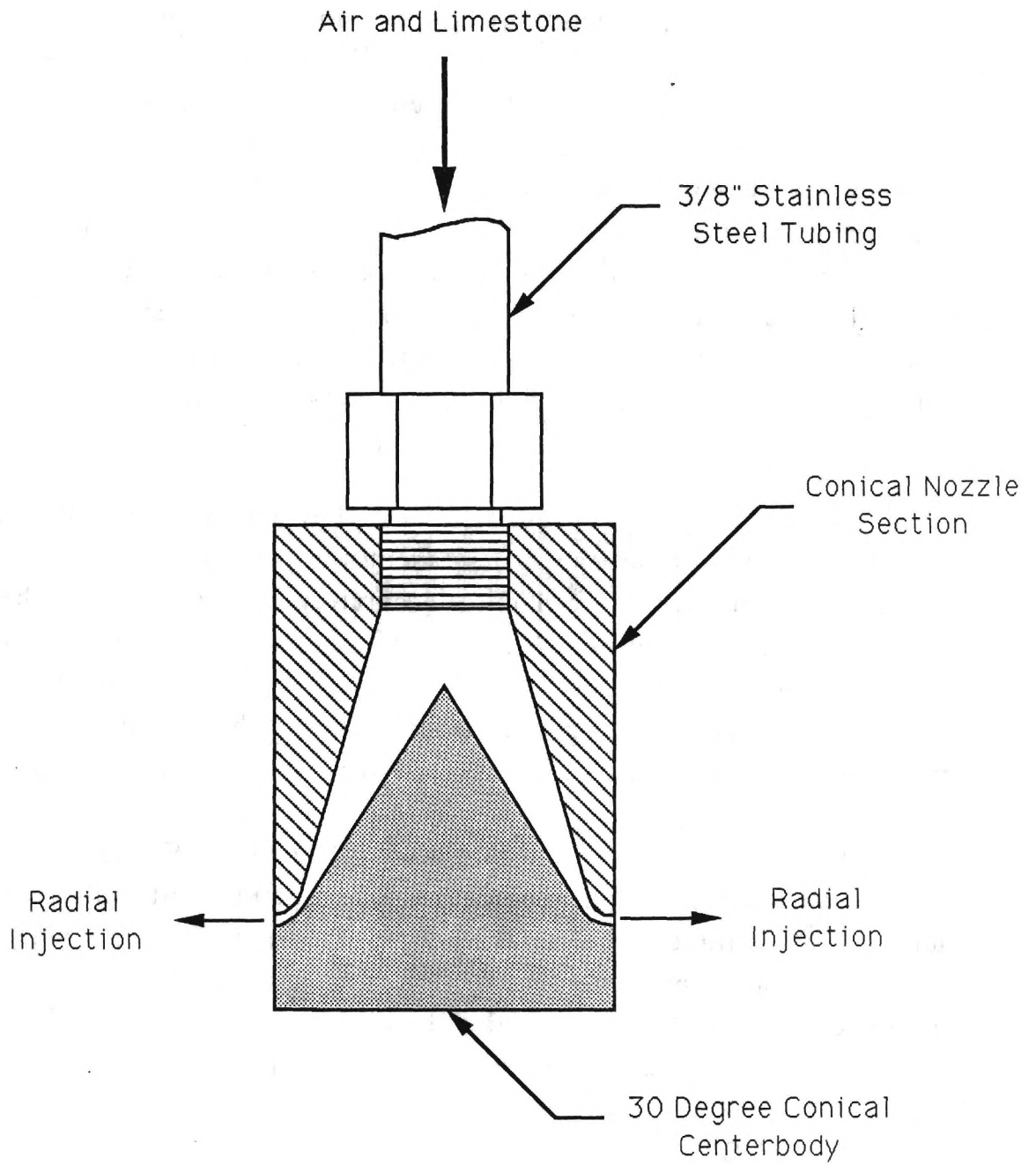


Figure 12. Limestone Injector Head

voltages were also input to the computerized A/D data analysis system.

A low impedance piezoelectric pressure transducer (Kistler Model 211B5) was installed in the combustor to measure the dynamic pressure amplitude or sound pressure level during pulsating operation. The transducer was installed at the middle level where the pressure amplitude is the greatest. To protect the transducer from the high temperature environment, the transducer was located in the side branch of a tee fitting connected to the combustor by a length of 0.64 cm diameter stainless steel tubing. The opposite end of the tee was connected to a 10 m long coiled section of soft plastic tubing to prevent acoustic resonances from occurring in the stainless steel tubing (i. e., by damping out reflections from the open end). The acoustic losses in the stainless steel tubing were determined to be about 2 dB, which were taken into account in the transducer calibration procedures. The output from the transducer was amplified and measured on a voltmeter and frequency counter for determination of the amplitude and frequency of the pressure oscillations, respectively. The transducer output was displayed on an oscilloscope for general observation of the wave shape. A DC voltage signal proportional to the RMS amplitude of the transducer output was also generated and used as input to the computerized data acquisition system.

## GAS ANALYSIS SYSTEM

During combustor operation the sampled exhaust gases are transferred through a heated stainless steel tube to the gas analyzer system. The concentrations of five chemical species in the exhaust gases are determined by the analyzer. The concentrations of carbon dioxide, carbon monoxide, and sulfur dioxide are determined by means of nondispersive infrared analyzers. A paramagnetic analyzer is used to determine the oxygen concentration, while the concentration of nitrogen oxides is determined by a chemiluminescent analyzer.

## BASELINE EXPERIMENTS

### EXPERIMENTAL PROCEDURE

A series of baseline experiments was conducted to determine the performance of the Rijke pulse combustor in the short configuration (3.05 m length) without combustion staging or sorbent addition. For these experiments the coal feed rate was 75 g/min and air/fuel ratios ranged from 0.6 to 1.5. These experiments were conducted according to the following procedure. Beginning with an empty bed, the combustor was preheated with propane for about five minutes under non-pulsating conditions. During the preheat phase, the propane flow rate was about 25 standard liters/min (SLM) and the air flow rate was about 1020 SLM. Next the bed rotation and coal feed were started while continuing to preheat with propane. After about two minutes, the coal was burning under non-pulsating conditions, and the primary air flow was adjusted for the desired air/fuel ratio and the propane was shut off. Immediately, pulsating operation began with pressure amplitudes of about 160 dB and a frequency of about 65 Hz. Oscilloscope traces of the acoustic pressure showed sinusoidal waveforms with little or no harmonic distortion. Pulsating operation was usually maintained for periods ranging from 15 to 25 minutes, but longer operating times were possible.

The onset of pulsating combustion is readily apparent from observations through the viewing windows. The flame height decreases drastically, the coal bed becomes fluidized and agitated by the acoustic velocity, and the intensity of the combustion increases as evidenced by the increased brightness of the combustion zone. A full view of the Rijke pulse combustor during a typical pulsating combustion experiment is shown in Figure 13. The three viewing windows in the vertical insulated combustion section are shown, where the lower window appears very bright due to the intense combustion zone extending above the coal bed. The coal feed system is to the left of the combustion section, while the decoupler is behind

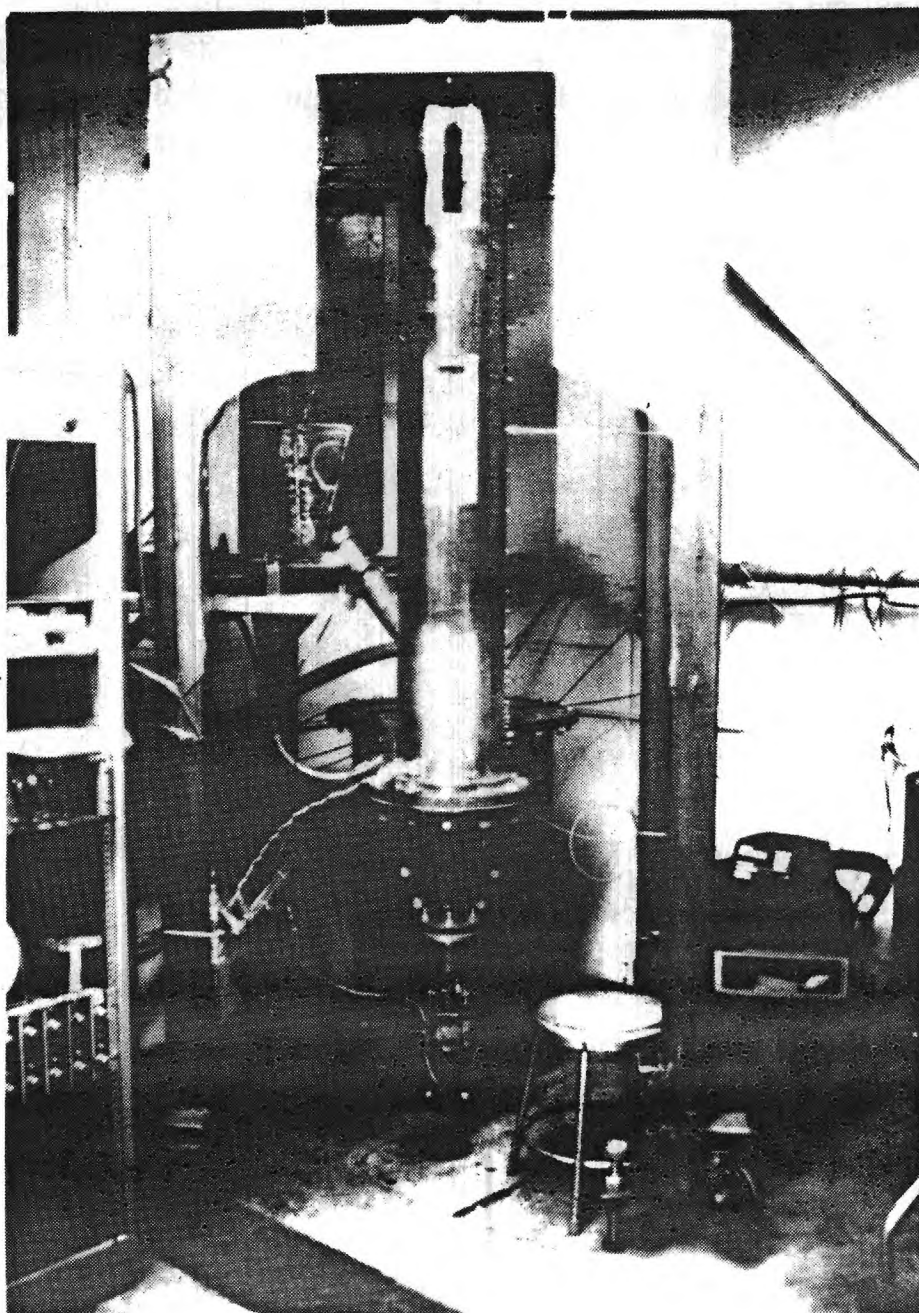


Figure 13. Photograph of Rijke Pulse Combustor During Pulsating Operation.

the combustor. The combustion section is suspended from a large steel frame with four legs with casters and leveling bolts, while the decoupler has its own set of casters. Figure 14 shows close-up views through the lower observation windows during nonpulsating (left) and pulsating (right) combustion of coal. In the pulsating case, pieces of coal and ash are visible several centimeters above the bed as a result of the extreme agitation caused by the large amplitude acoustic velocity oscillations through the bed. The acoustic velocity oscillations also caused flamelets to periodically extend below the coal bed grid during each oscillation cycle. These appear to be stationary to the eye since the flamelets oscillate at about 65 Hz. Figure 15 gives an oblique view upward through the lower part of the bed observation window showing these flamelets.

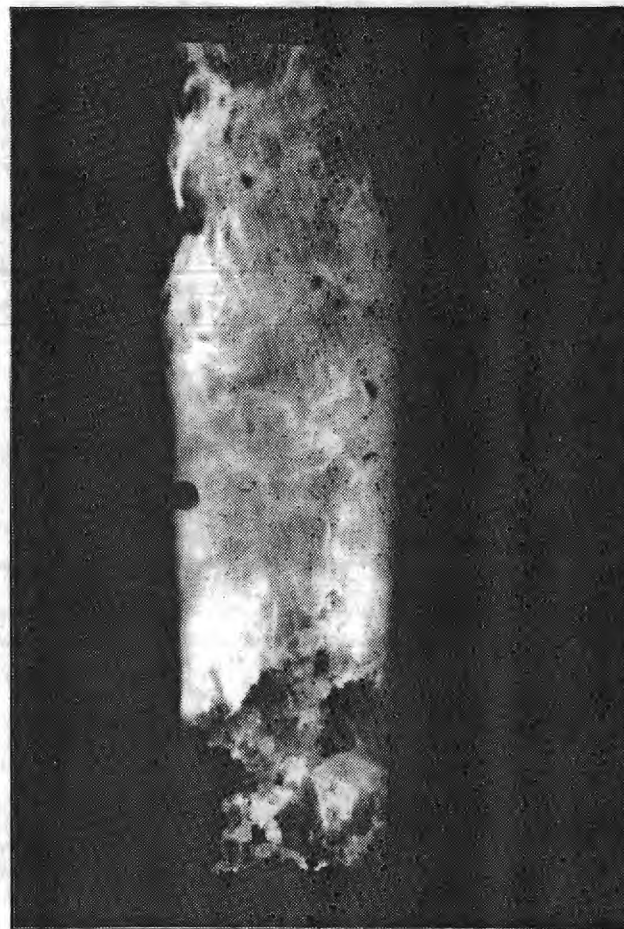
## COAL PROPERTIES

The coal used in all of the experiments was a bituminous coal obtained from Georgia Power Company's Plant McDonough located near Atlanta. This coal was obtained from a large pile which had recently been delivered from a single trainload. The coal as received had a wide range of particle sizes, from coal dust (less than 0.1 mm) to large lumps several centimeters across.

A representative sample of the coal obtained from Plant McDonough was subjected to proximate and ultimate analysis. The proximate analysis was performed at the Central Test Laboratory of Georgia Power Company, while the ultimate analysis was performed by the General Test Laboratory of the Alabama Power Company. These analyses were obtained at no cost to the project. The results of the analyses are presented in Table I. In performing the proximate analysis, the sample as received was first air-dried for 12 hours at 40 C. An 8-mesh sample was extracted, and the remainder was ground to 60-mesh. The 60-mesh sample was heated for 1 hour at 104 C, while the 8-mesh sample was heated for 1.5 hours at the same temperature. This yielded a 60-mesh moisture content of 1.84 percent and an 8-mesh moisture content of 1.63 percent. The 60-



Preheating with Propane



Pulsating

Figure 14. Photographs of Combustion Zone During Preheating and Pulsating Combustion of Coal.



Figure 15. Photograph of Oscillatory Flamelets Extending Below Bed During Pulsating Combustion of Coal.

mesh sample was then subjected to proximate analysis to yield the "As Determined" values in Table I. The "As Received" values were calculated on the basis of the moisture loss during the preliminary air drying. The 8-mesh and 60-mesh moisture values were used in calculating the dry basis values. The heating value of the coal as received was 29,060 kJ/kg.

Table I. Coal Analysis

PROXIMATE ANALYSIS			
Analysis	As Determined	As Received	Dry
Moisture	2.05	5.60	-
Volatiles	33.19	31.98	33.88
Ash	11.08	10.68	11.31
Fixed Carbon	53.68	51.74	54.81
Sulfur	1.31	1.26	1.33

ULTIMATE ANALYSIS		
Analysis	As Determined	Dry
Carbon	72.20	73.85
Hydrogen	5.09	4.95
Nitrogen	1.48	1.51
Sulfur	1.31	1.33
Oxygen	6.60	7.03
Ash	11.08	11.33
Moisture (60 mesh)	2.24	-

In order to obtain consistency in the size distribution of the coal lumps burned in the Rijke pulse combustor, a large sieve was constructed for sizing the coal. This sieve consists of a wooden frame with a hinged lid. The bottom of the frame holds a hardware cloth screen to retain coal particles larger than about 6 mm in diameter.

The coarser screen on the lid retains coal lumps larger than about 12 mm in diameter. The sieve fits over the top of an empty 55-gallon drum which catches the fine particles which fall through the lower screen. The coarser lumps are retained on the upper screen and are stored separately for later crushing. The particles between the screens, which are between 6 mm and 12 mm in diameter, are then transferred to drying boards and later stored for use in the combustor.

## BASELINE RESULTS

For each of the baseline tests, sound pressure levels, frequencies, exhaust gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and gas temperatures were measured as a function of the dimensionless air/fuel ratio ( $\alpha$ ) for a fixed coal feed rate of 75 g/min. Measurements were recorded every six seconds during a typical experiment lasting about 15 - 20 minutes. A total of 22 baseline experimental runs were conducted with at least two runs for each value of the dimensionless air/fuel ratio.

Plots of the measured sound pressure level and exhaust gas species concentration values as a function of elapsed time are shown in Figures 16, 17 and 18 for a typical baseline experiment with a dimensionless air/fuel ratio of 1.00 (stoichiometric combustion). The sound pressure levels shown in Figure 16 indicate that the pulsation amplitude was nearly constant during the entire experiment; the variation in amplitude was less than 0.7 dB above or below the mean amplitude of 159.8 dB. The concentrations of carbon dioxide, oxygen, and carbon monoxide in the exhaust gases during this experiment are shown in Figure 17. After an initial transient period of about five minutes, the concentrations of these gases attained nearly constant values for the remainder of the test. The concentration of carbon dioxide reached a steady value of 16.2 percent by volume, while the concentration of residual oxygen was reduced essentially to zero. This indicates nearly complete combustion of the coal during pulsating operation. The concentration of carbon monoxide averaged

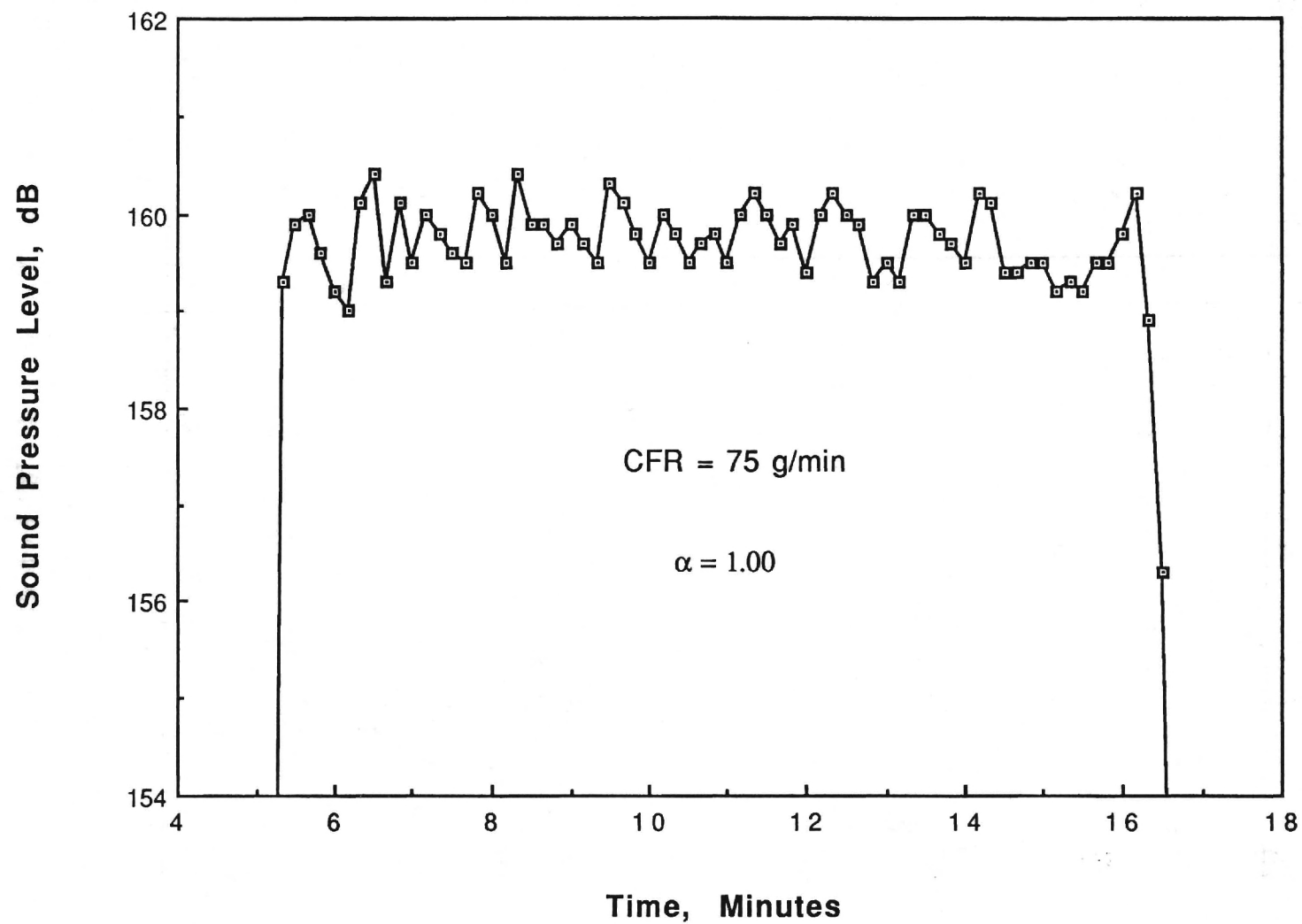


Figure 16. Sound Pressure Levels for a Typical Baseline Experiment.

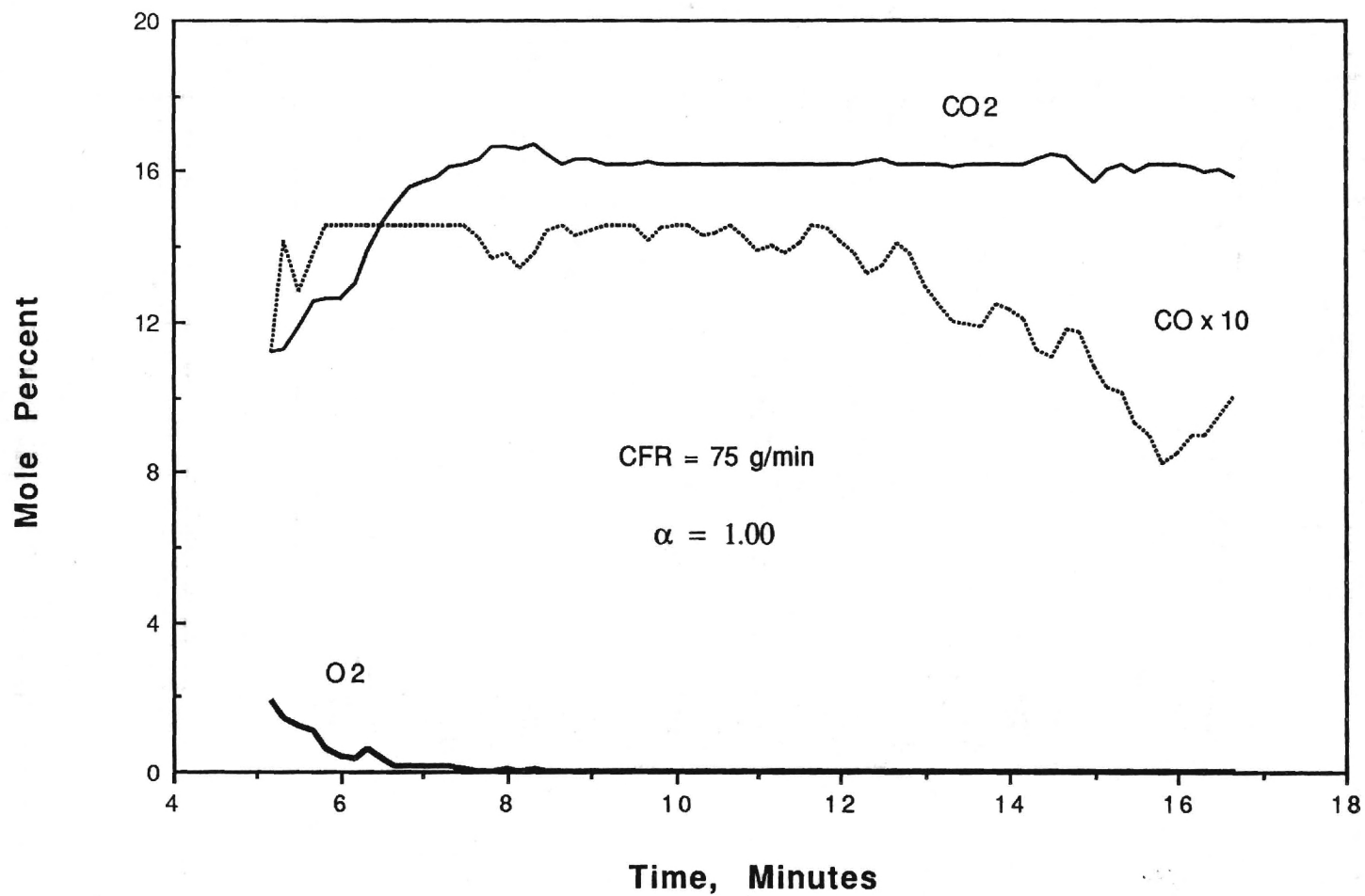


Figure 17. Exhaust Gas Carbon Dioxide, Oxygen, and Carbon Monoxide Concentrations for a Typical Baseline Experiment.

about 1.4 percent during the middle of the experiment, and it decreased significantly during the later stages of the test. The high levels of CO indicate that a small amount of excess air is needed for good combustion efficiency of this system. The emissions of nitrogen oxides and sulfur dioxide for this experiment are presented in Figure 18. Both  $\text{NO}_x$  and  $\text{SO}_2$  concentrations exhibited sharp peaks during the transient period, but soon reached steady state values. The  $\text{NO}_x$  concentration averaged about 360 ppm by volume during the early phases of the run and gradually increased to about 425 ppm toward the end of the test. The  $\text{SO}_2$  concentration fluctuated about a mean of about 1300 ppm during the experiment. During this experiment the agglomerates were continuously broken up by the action of the rotating bed, and the distribution of coal on the bed was very uniform. Furthermore, the ash particles were ground down to small enough sizes so that they continuously fell through the bed grid, thus preventing accumulation of coal and ash on the bed.

Since the measured quantities fluctuated with time during the 15-20 minute experiments, data was time averaged over two or three time periods (each lasting 3-5 minutes) for each test. Plots of the measured quantities as a function of time were used to determine which one of the time averages was more typical of the experiment. This procedure determined a representative value for each of the measured quantities for each experiment. For each dimensionless air/fuel ratio, the time averaged data from the appropriate experiments were then averaged and tabulated. The results of the baseline experiments are summarized in Table II. Plots were generated of each quantity as a function of  $\alpha$ ; these are given in Figures 19 through 21.

Sound pressure level and frequency as a function of  $\alpha$  are shown in Figure 19. Sound pressure level was a maximum, about 160 dB, for stoichiometric conditions ( $\alpha = 1.00$ ). The lowest amplitude recorded was 156 dB at dimensionless air/fuel ratios of 0.6 and 0.7. The pulsation frequency increased as the dimensionless air/fuel ratio was increased, ranging from about 64 Hz at  $\alpha = 0.6$  to

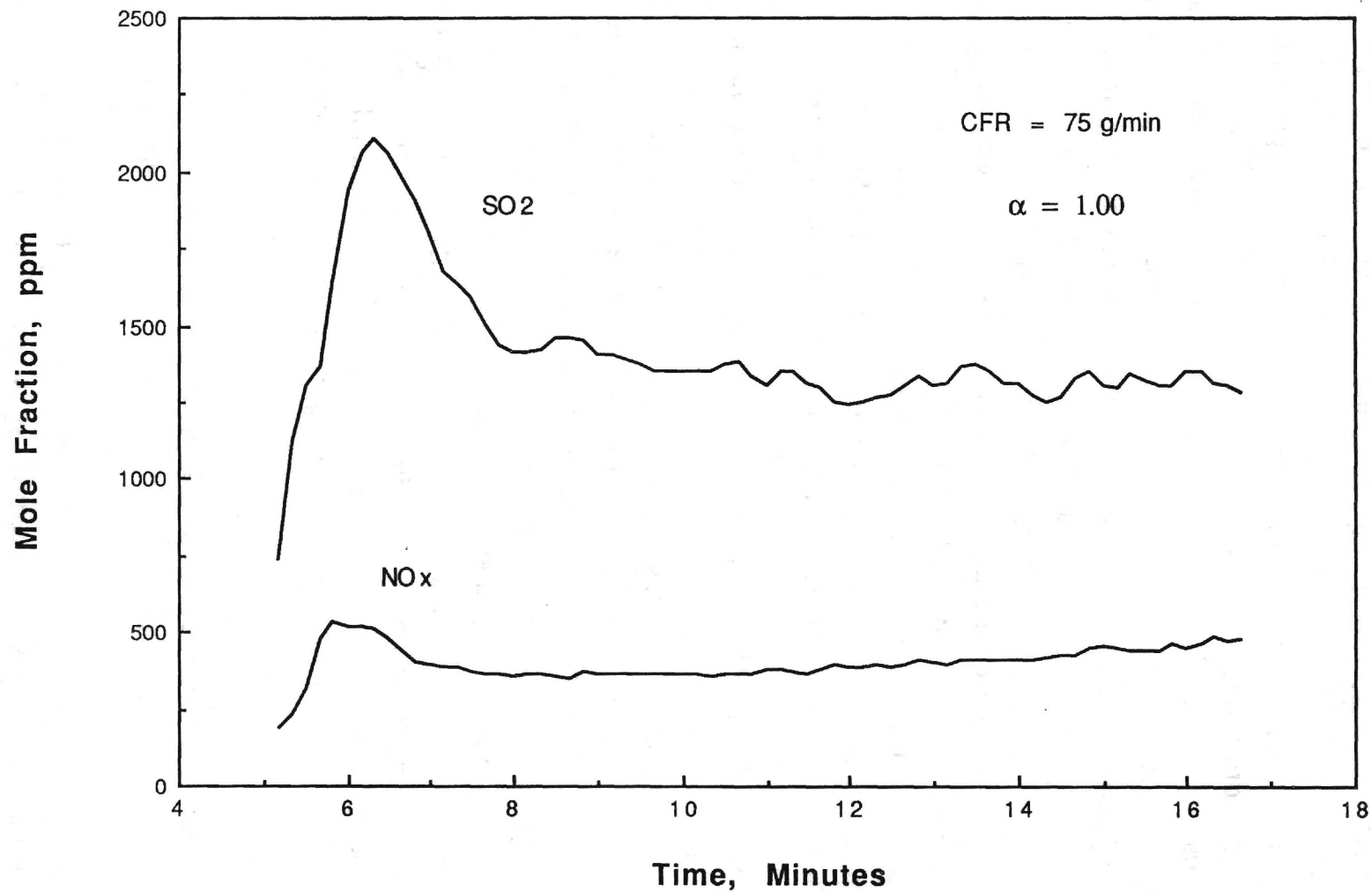


Figure 18. Nitrogen Oxides and Sulfur Dioxide Emissions for a Typical Baseline Experiment.

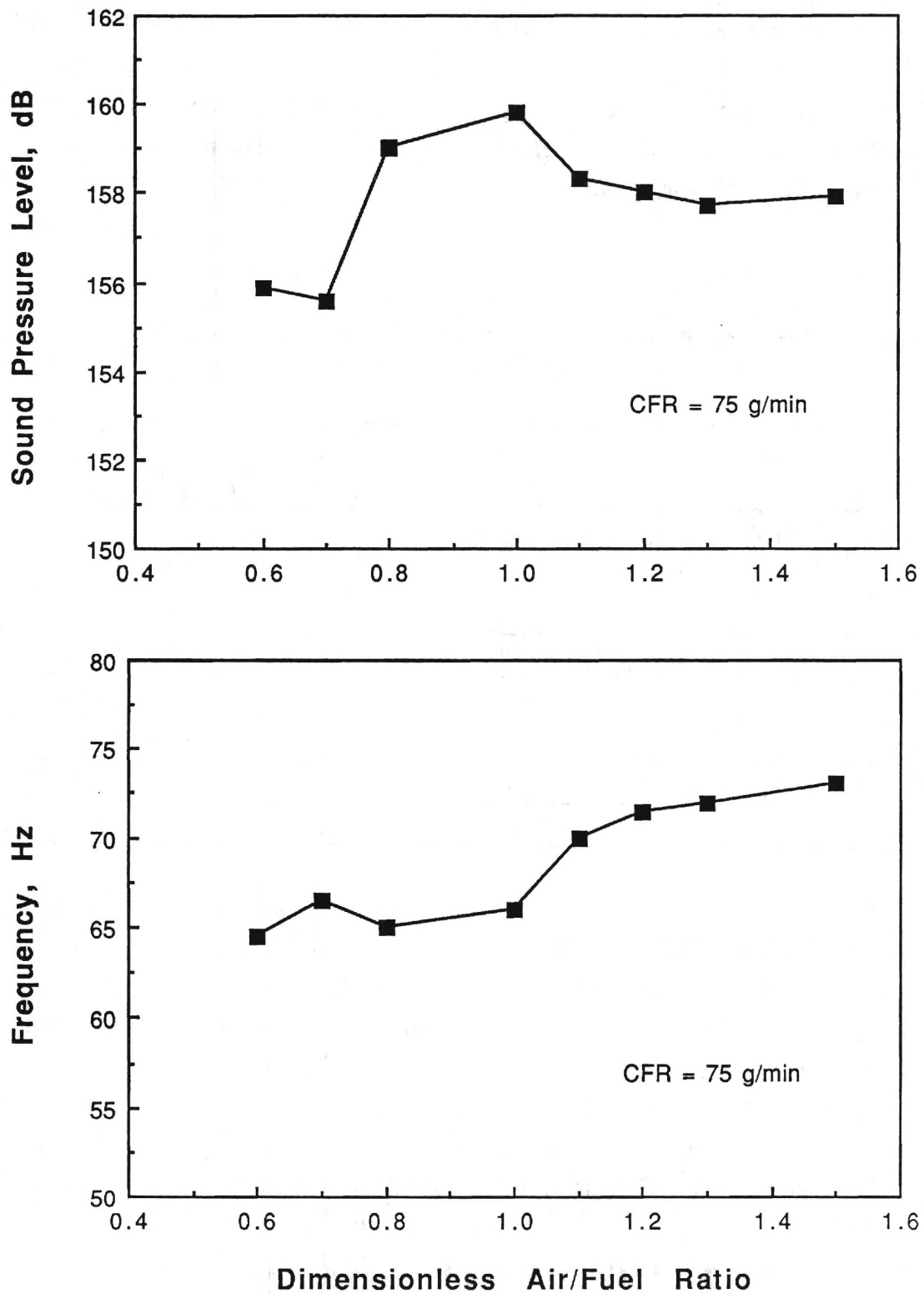


Figure 19. Dependence of Baseline Sound Pressure Levels and Frequencies on Dimensionless Air/Fuel Ratio.

about 73 Hz at  $\alpha = 1.5$ . These frequencies are consistent with the fundamental longitudinal acoustic mode of the open-ended Rijke tube combustor. The changes in frequency with dimensionless air/fuel ratio are due to changes in the temperature distribution and composition of the gases in the region between the coal bed and the exhaust outlet.

Table II. Averaged Sound Pressure Levels, Frequencies and Exhaust Compositions for Baseline Experiments.

No. of Tests	$\alpha$	SPL (dB)	Freq (Hz)	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)
2	0.6	155.9	64.5	15.4	1.12	484	NA	0.29
5	0.7	155.6	66.5	14.5	0.73	451	1420	1.36
2	0.8	159.0	65.0	16.2	1.01	398	1450	0.04
4	1.0	159.8	66.0	16.6	0.83	443	1420	0.65
2	1.1	158.3	70.0	16.5	0.42	502	1480	0.52
2	1.2	158.0	71.5	15.1	0.05	585	1270	3.16
2	1.3	157.7	72.0	10.5	0.02	592	1140	5.83
2	1.5	157.9	73.0	11.3	0.06	559	940	6.47

Carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), and residual oxygen (O<sub>2</sub>) concentrations are shown in Figure 20. Carbon dioxide levels were maximum (16.5 percent) for stoichiometric conditions, and they were above 16 percent for dimensionless air/fuel ratios between 0.8 and 1.1. Carbon monoxide concentrations ranged between 0.7 and 1.2 percent for stoichiometric and fuel rich combustion, but CO levels dropped sharply when excess air was added, becoming less than 0.06 percent for  $\alpha = 1.2$  or greater. For dimensionless air/fuel ratios below 1.1, residual oxygen concentrations were small (less than one percent), but they increased sharply as excess air was increased, reaching 6 to 6.5 percent for dimensionless air/fuel ratios of 1.3 and above.

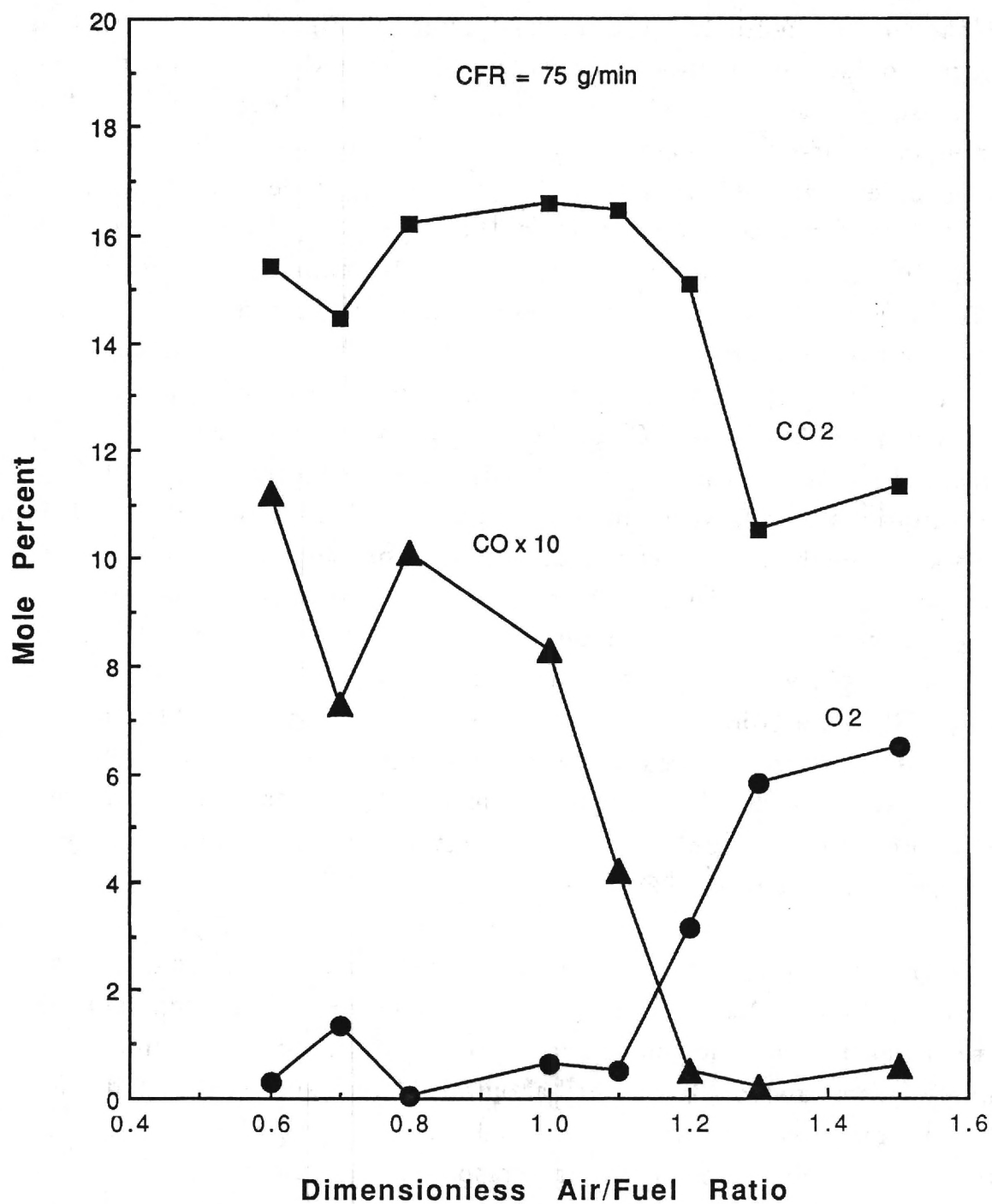


Figure 20. Effect of Dimensionless Air/Fuel Ratio on Baseline Exhaust Concentrations of Carbon Dioxide, Carbon Monoxide and Oxygen.

Nitrogen oxides ( $\text{NO}_x$ ) and sulfur dioxide ( $\text{SO}_2$ ) concentrations are shown in Figure 21. The upper graph in Figure 21 shows that nitrogen oxides production was between 400 and 600 ppm for the entire range of dimensionless air/fuel ratios investigated. The maximum concentration of  $\text{NO}_x$  (about 590 ppm) was obtained for dimensionless air/fuel ratios of 1.2 and 1.3, while minimum  $\text{NO}_x$  (about 400 ppm) occurred at  $\alpha = 0.8$ . This graph also shows that sulfur dioxide concentrations were near 1450 ppm for dimensionless air/fuel ratios below 1.1, and they decreased steadily for larger air/fuel ratios primarily due to the dilution effect of the excess air. To remove this dilution effect and allow comparison with other data, the measured  $\text{NO}_x$  and  $\text{SO}_2$  concentrations were reduced to a 15% excess air (3% excess oxygen) basis. The reduced  $\text{NO}_x$  and  $\text{SO}_2$  concentrations are shown in the lower graph of Figure 21. This reveals a much more pronounced effect of dimensionless air/fuel ratio on the  $\text{NO}_x$  emissions from the pulse combustor. The reduced  $\text{NO}_x$  concentrations were about 250 ppm for  $\alpha$  below 0.8, they increased rapidly as  $\alpha$  increased from 0.8 to 1.3, and they reached about 725 ppm for  $\alpha = 1.5$ . The reduced  $\text{SO}_2$  concentrations exhibited a strong increase with increasing dimensionless air/fuel ratio for  $\alpha$  less than 1.1, ranging from about 850 ppm to 1400 ppm. For higher dimensionless air/fuel ratios, there was a gradual decrease in the reduced  $\text{SO}_2$  concentration.

The gas temperature profiles for the baseline experiments are shown in Figure 22. For most of the experiments, gas temperatures were measured at the combustor axis at four to seven locations, ranging from about 20 cm to about 155 cm above the bed. The highest temperatures were measured for a dimensionless air/fuel ratio of 1.1, with slightly lower temperatures obtained for the larger air/fuel ratios ( $1.2 < \alpha < 1.5$ ). These temperatures decreased nearly linearly with increasing height above the bed, ranging from about 1000 C at 30 cm above the bed to about 800 C near the upper end of the combustion section (120 cm). This decline in temperature resulted from heat losses through the combustor walls. As the dimensionless air/fuel ratios were lowered below  $\alpha = 1.1$ , the gas

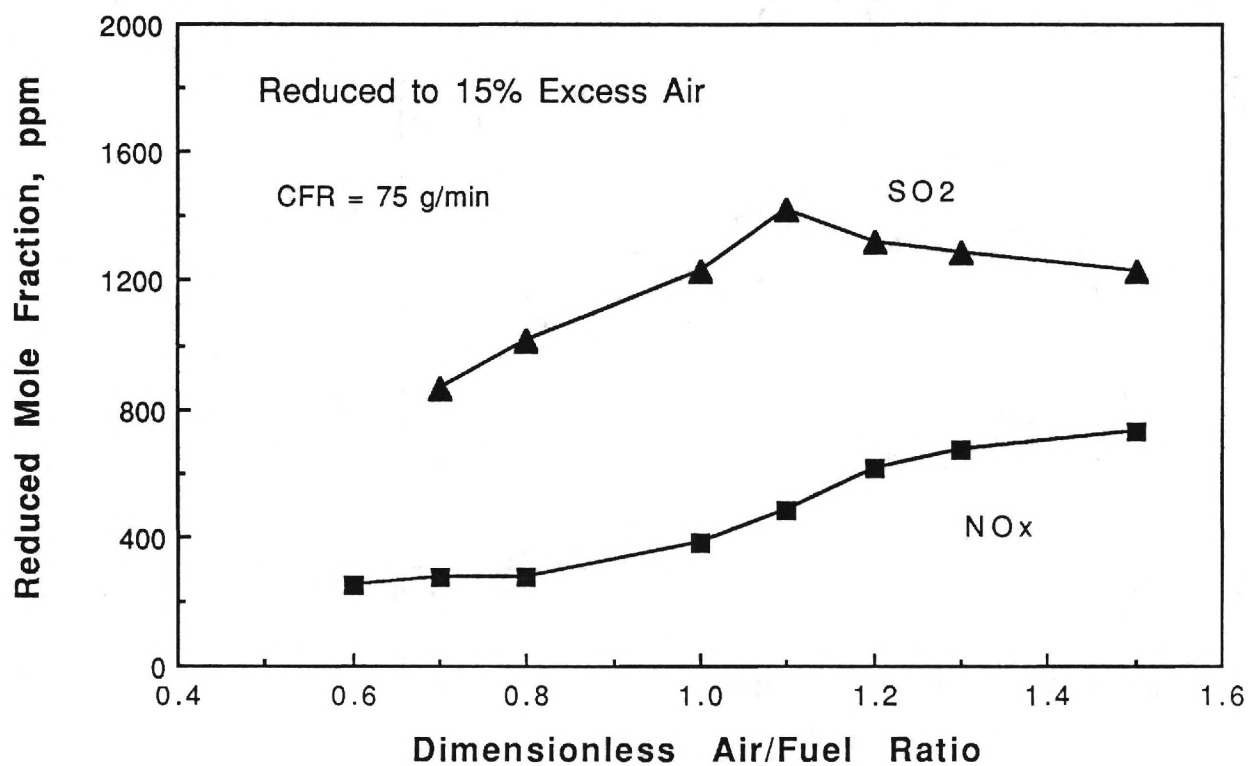
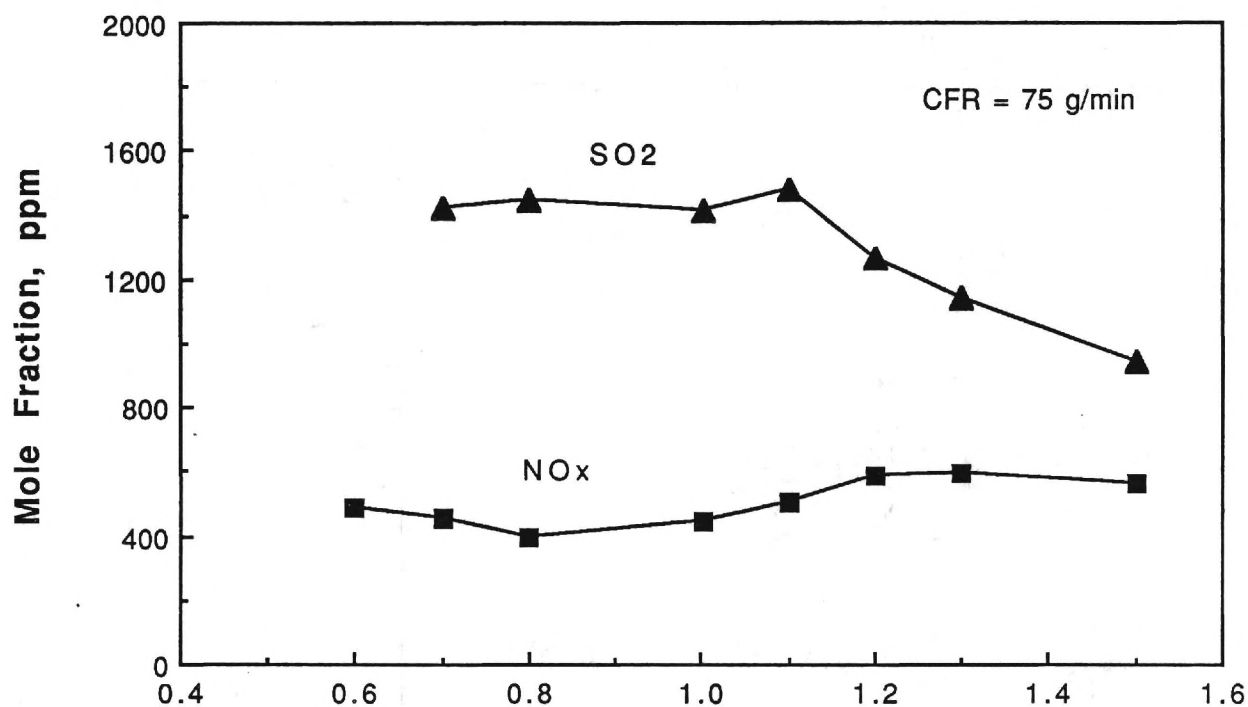


Figure 21. Effect of Dimensionless Air/Fuel Ratio on the Baseline Emissions of Nitrogen Oxides and Sulfur Dioxide.

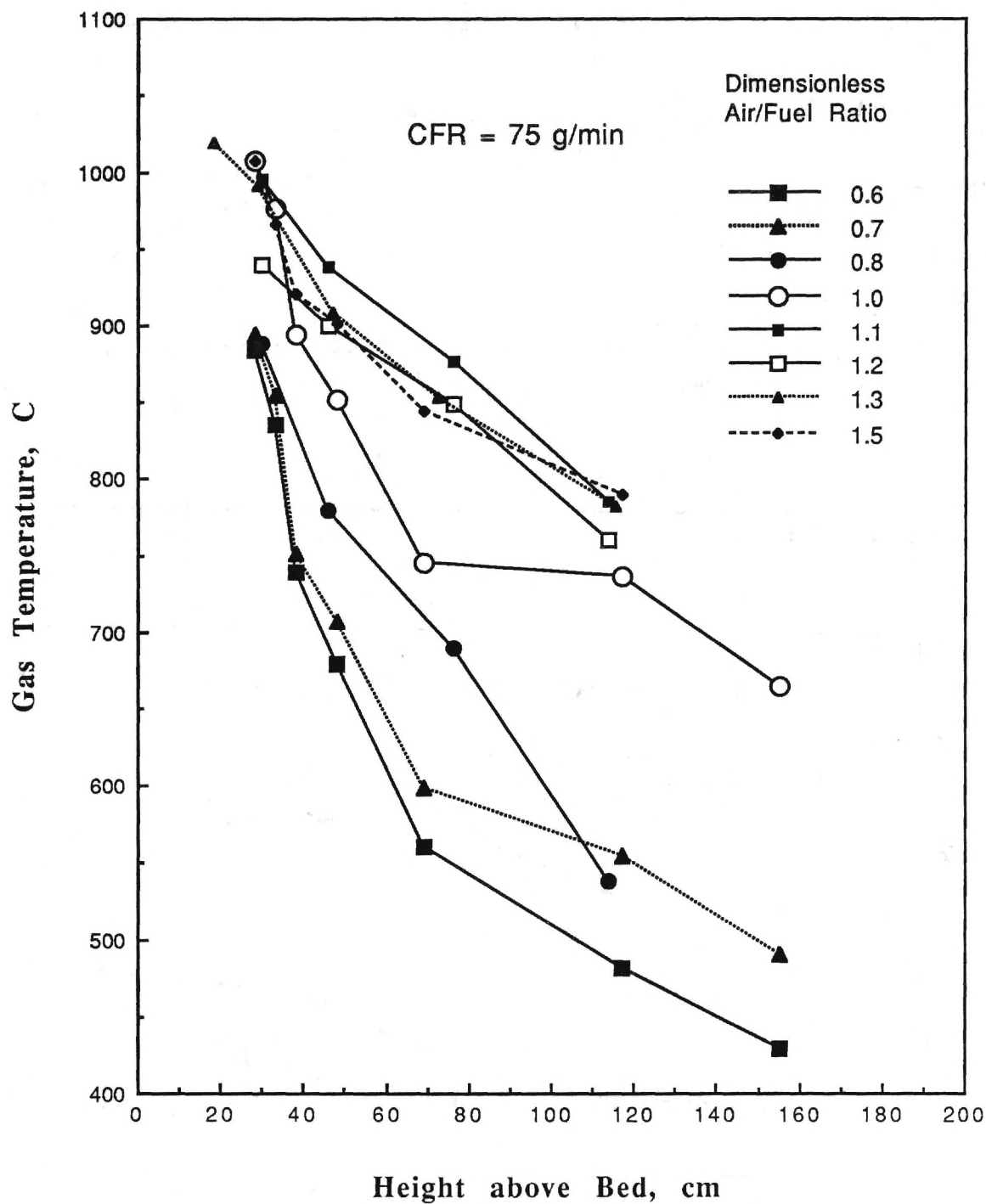


Figure 22. Baseline Gas Temperature Profiles.

temperatures at the lowest levels decreased by moderate amounts (about 100 C), while at higher levels the temperature decrease was much larger (about 200 to 300 C). For dimensionless air/fuel ratios in the range  $0.6 < \alpha < 1.0$ , the temperature profiles were nonlinear, being characterized by a much steeper decline in temperature in the lower half of the combustor and a more gradual decline in temperature in the upper half of the combustion section. The lowest gas temperatures were obtained for a dimensionless air/fuel ratio of 0.6; these ranged from about 900 C at 30 cm above the bed to about 425 C at the upper end of the combustion section (155 cm).

## AIR STAGING EXPERIMENTS

Two groups of air staging experiments were conducted during this investigation. In these experiments the coal was burned in the primary combustion zone under fuel rich (gasification) conditions, and secondary air was introduced some distance above the bed (secondary combustion zone) to complete the combustion of the fuel gases (CO, CH<sub>4</sub>, H<sub>2</sub>, etc) produced by devolatilization processes in the primary combustion zone. The stoichiometry of the primary combustion zone was specified by the dimensionless primary air/fuel ratio,  $\alpha_1$ , which was always less than unity. The overall stoichiometry of the entire air-staged combustion process was determined by the total dimensionless air/fuel ratio,  $\alpha_t$ . In the first series of air staging experiments, the total air/fuel ratio,  $\alpha_t$ , was equal to one. The second group of air staging experiments was conducted with total air/fuel ratios greater than one.

### AIR STAGING EXPERIMENTS WITH $\alpha_t$ OF UNITY

In this series of air-staging tests, the secondary air was injected at three heights above the bed: 20 cm, 27 cm, and 37 cm. The secondary air supply system and injector are shown in Figure 3. In each experiment the total air/fuel ratio ( $\alpha_t$ ) was stoichiometric, that is,  $\alpha_t = 1.00$ . Each of these experiments were divided into three

segments lasting about five minutes each. In the first segment, a primary air/fuel ratio of 1.0 was used (no secondary air injection). The primary air/fuel ratio was then reduced to 0.7 in the second segment and to 0.5 in the third segment. Time averaged values of sound pressure levels, frequencies, exhaust gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and temperatures were obtained for each segment.

A total of nine air staging experiments were conducted in this series. Two experiments were conducted with secondary air injection at 37 cm above the bed, three experiments were run with air staging at 27 cm above the bed, and four experiments were conducted with air staging at 20 cm above the bed. For each secondary air injection height and each primary air/fuel ratio,  $\alpha_1$ , the time averages of each of the measured quantities for the appropriate experiments were averaged. The resulting values were then tabulated and plotted as a function of the primary air/fuel ratio,  $\alpha_1$ , for the three secondary injection heights above the bed. These data are presented in Table III and Figures 23 through 28.

Figure 23 shows that sound pressure levels increased nearly linearly from 154 dB at  $\alpha_1 = 0.5$  to about 160 dB at  $\alpha_1 = 1.0$ . Secondary air injection height had very little affect on the amplitude and frequency of the pulsations.

Carbon dioxide concentrations for the air staging experiments are shown in Figure 24. Except for the lowest secondary air injection point (20 cm), the  $\text{CO}_2$  concentration increased monotonically with increasing primary dimensionless air/fuel ratio. Carbon dioxide concentrations ranged between 12.5 percent and nearly 16 percent, with the lower values corresponding to  $\alpha_1 = 0.5$ . Except for the unexpected decrease in  $\text{CO}_2$  concentration for secondary air injection at 20 cm,  $\text{CO}_2$  concentrations increased only slightly between  $\alpha_1 = 0.7$  and  $\alpha_1 = 1.0$ . The concentration of  $\text{CO}_2$  also decreased significantly with increasing height of the secondary air injection point. Carbon dioxide concentrations measured in the air staging experiments at  $\alpha_1 = 1.0$  were somewhat lower than those measured in the baseline

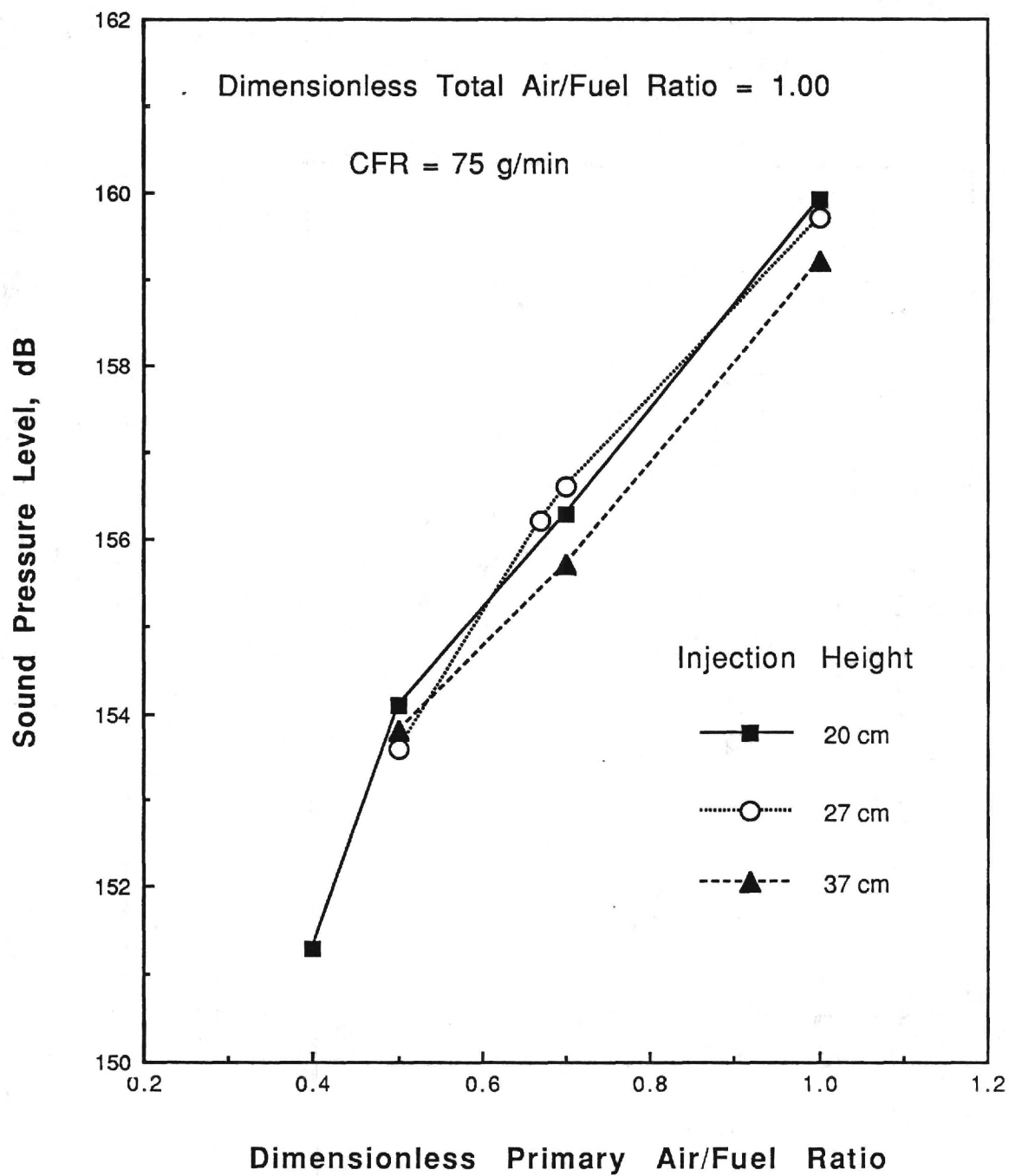


Figure 23. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on Pulsation Amplitude.

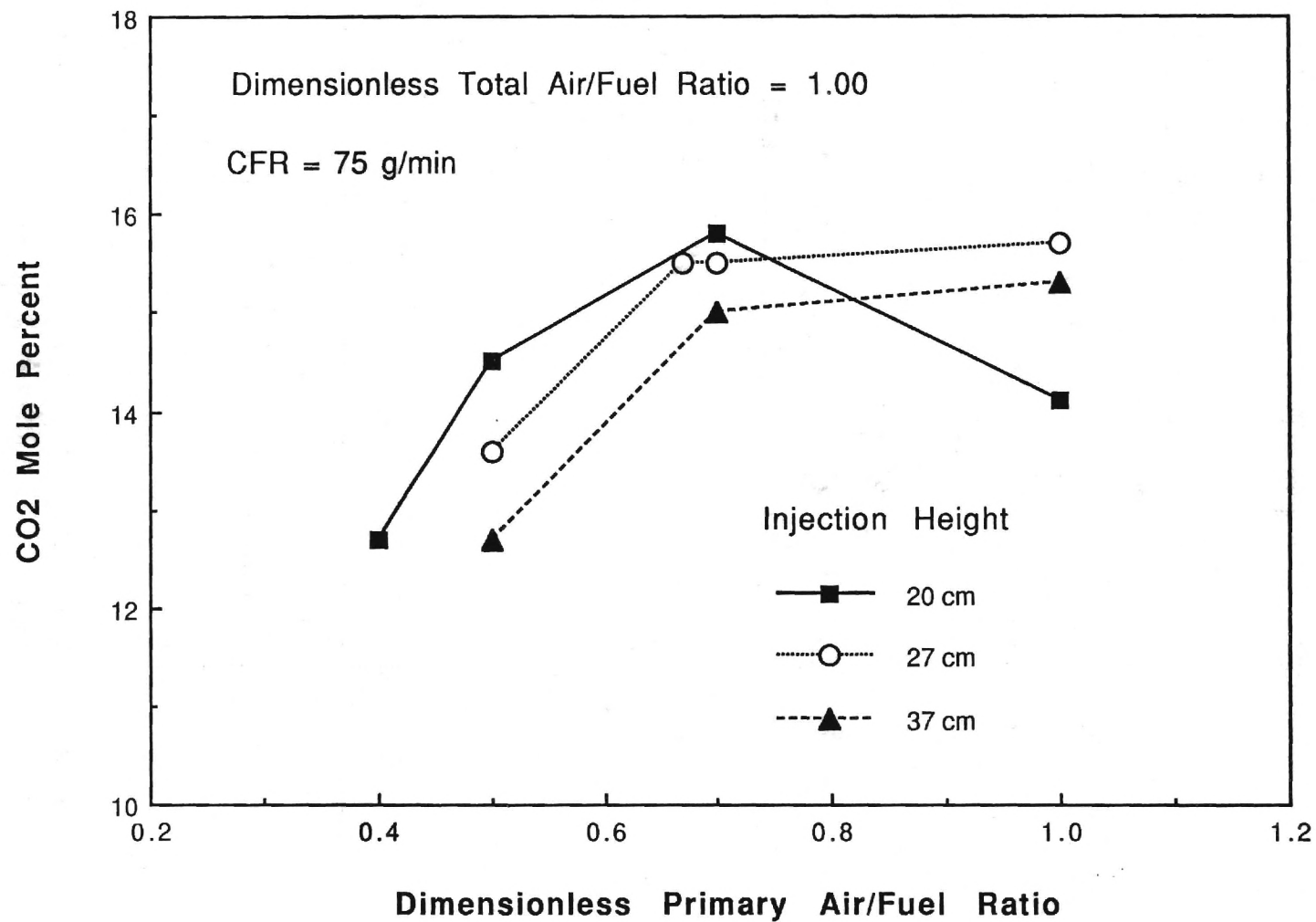


Figure 24. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on the Exhaust Carbon Dioxide Concentration.

experiments at stoichiometric combustion conditions. This was probably due to the dilution effect of a small amount of secondary air used to cool the injection head for the case of  $\alpha_1 = 1.0$ .

Table III. Averaged Sound Pressure Levels and Exhaust Gas Compositions for Air Staging Experiments with  $\alpha_1 = 1.00$ .

Air Staging Location (cm)	$\alpha_1$	SPL (dB)	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)
20	0.4	151.3	12.7	0.05	597	1190	5.7
	0.5	154.1	14.5	0.20	555	1230	4.1
	0.7	156.3	15.8	0.15	535	1260	2.8
	1.0	159.9	14.1	0.58	505	1470	2.3
27	0.5	153.6	13.6	0.05	453	1170	4.5
	0.67	156.2	15.5	0.05	498	1300	3.1
	0.7	156.6	15.5	0.10	516	1210	2.7
	1.0	159.7	15.7	0.45	485	1310	1.8
37	0.5	153.8	12.7	0.10	429	1090	5.2
	0.7	155.7	15.0	0.15	454	1250	3.0
	1.0	159.2	15.3	0.35	471	1310	2.1

The measured carbon monoxide emissions for the air staging experiments are shown in Figure 25. Carbon monoxide concentration generally increased with increasing dimensionless primary air/fuel ratio. Carbon monoxide concentration varied between about 0.05 and 0.6 percent, with the higher values for  $\alpha_1 = 1.0$  (no secondary air injection). Increasing the secondary air injection height generally reduced the amount of CO in the exhaust gases. The CO concentrations measured in the air staging tests for  $\alpha_1 = 1.0$  were generally lower than those measured in the baseline experiments under stoichiometric combustion conditions.

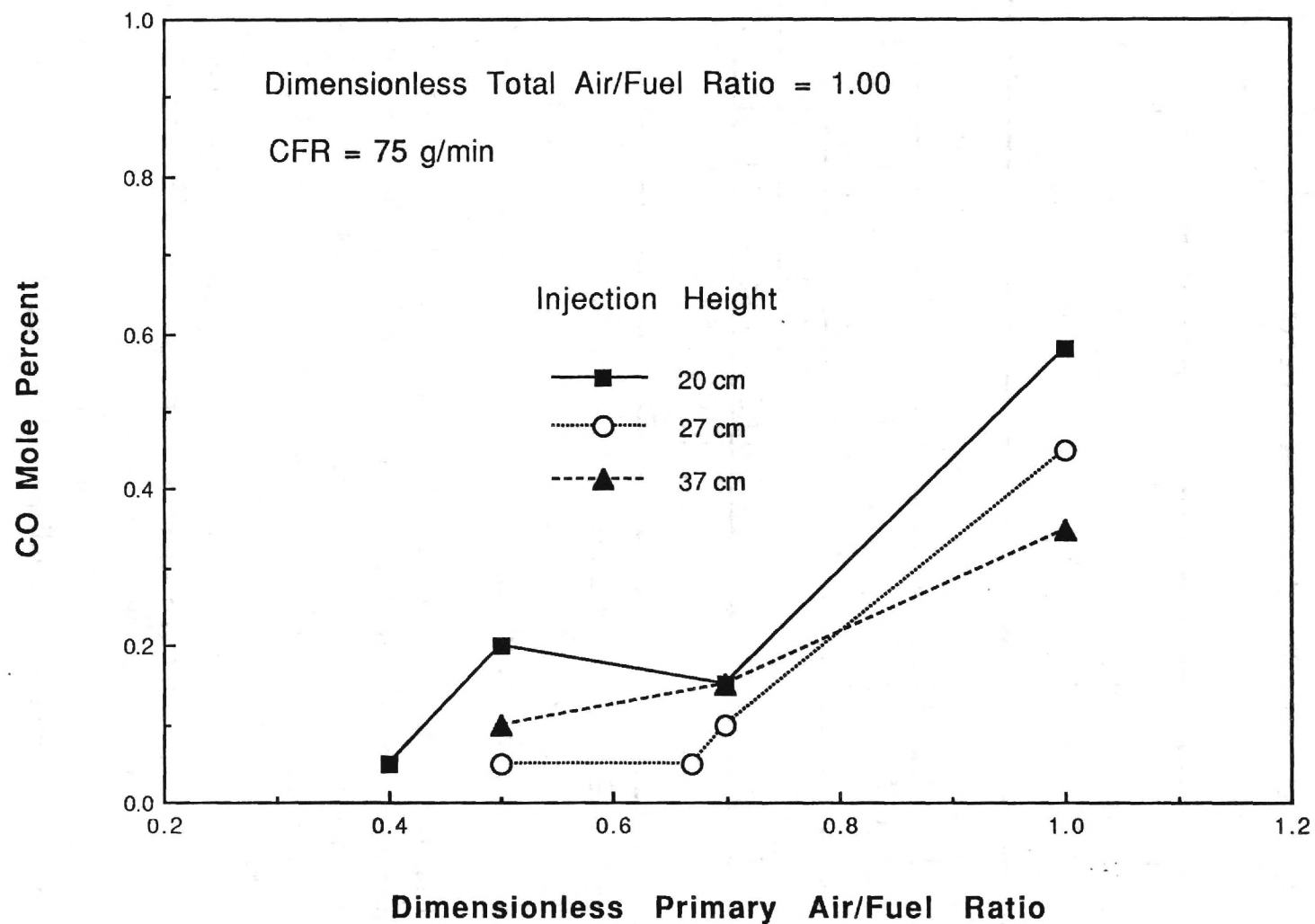


Figure 25. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on the Exhaust Carbon Monoxide Concentration.

Measured oxygen concentrations in the exhaust gases during the air staging experiments are shown in Figure 26. Residual oxygen levels were higher for lower values of the primary air/fuel ratio, with a maximum of 5.7 percent for  $\alpha_1 = 0.4$  with secondary air injection at 20 cm above the primary combustion zone. For  $\alpha_1 = 1.0$ , residual oxygen was about 2 percent. Residual oxygen levels generally increased as the secondary air injection height was increased. These residual oxygen levels indicate that combustion of the coal gases by the secondary air injection was not complete, since the total air/fuel ratio was stoichiometric. Residual oxygen concentrations in the air staging tests for  $\alpha_1 = 1.0$  were somewhat higher than those measured in the baseline experiments under stoichiometric combustion conditions.

The measured nitrogen oxides concentrations in the exhaust gases for the air staging experiments are shown in Figure 27. Nitrogen oxides emissions ranged between 400 ppm and 600 ppm with only moderate reductions due to air staging. For secondary air injection at 20 cm above the bed, decreasing  $\alpha_1$  increased the  $\text{NO}_x$  concentrations, but reducing  $\alpha_1$  yielded slight decreases in the  $\text{NO}_x$  emissions for the higher injection points. Increasing the height of the secondary air injection point resulted in decreased  $\text{NO}_x$  emissions, especially for the smaller primary air/fuel ratios.

Although the object of the air staging experiments was the reduction of  $\text{NO}_x$  emissions, the effect of air staging on sulfur dioxide emissions was also obtained. These results are shown in Figure 28. At the lowest secondary air injection point, sulfur dioxide emissions ranged from about 1200 ppm for  $\alpha_1 = 0.4$  to nearly 1500 ppm for  $\alpha_1 = 1.0$ . Raising the secondary injection point clearly decreased  $\text{SO}_2$  emissions for  $\alpha_1 = 0.5$  but had little effect on  $\text{SO}_2$  concentrations for  $\alpha_1 = 0.7$ .

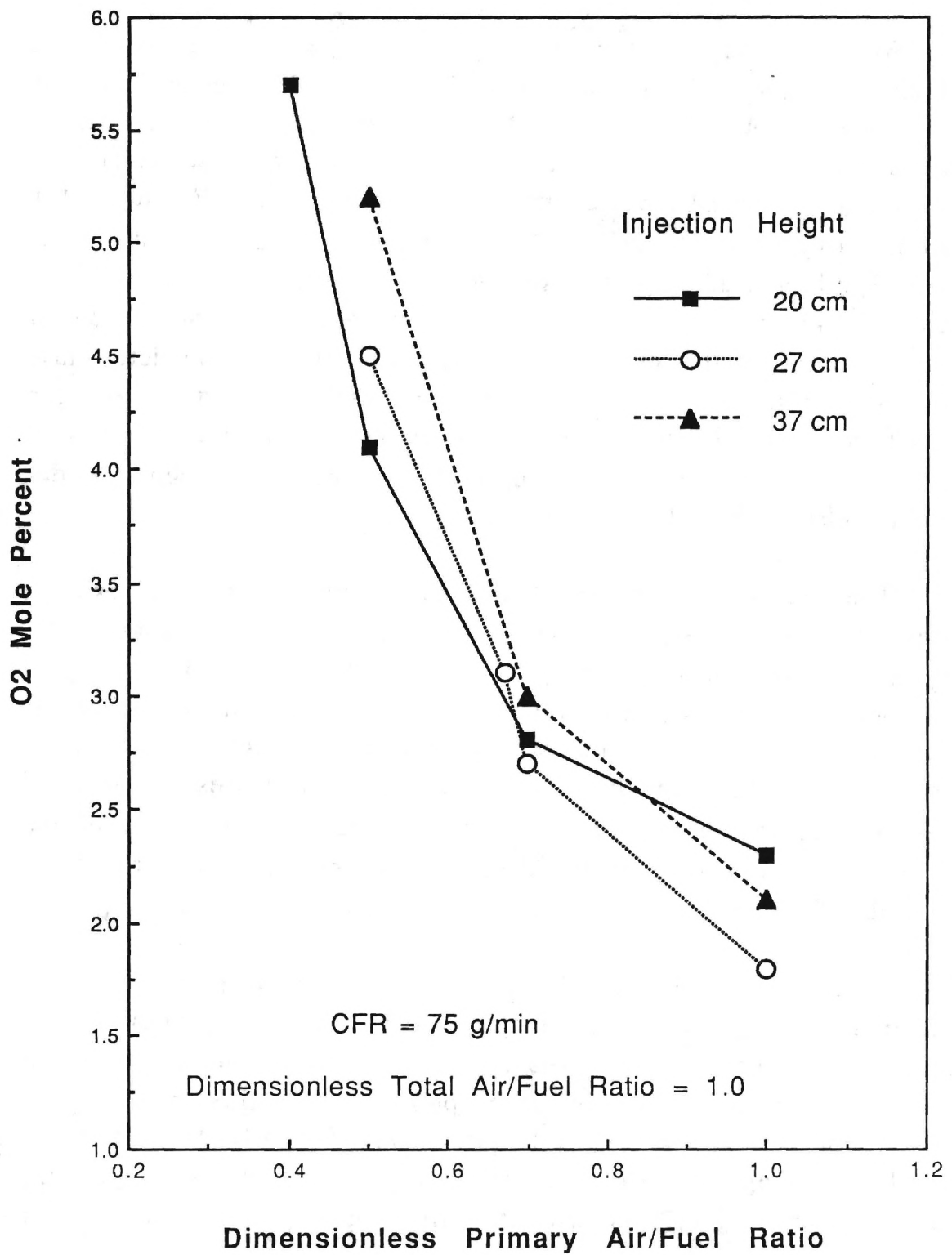


Figure 26. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on the Exhaust Oxygen Concentration.

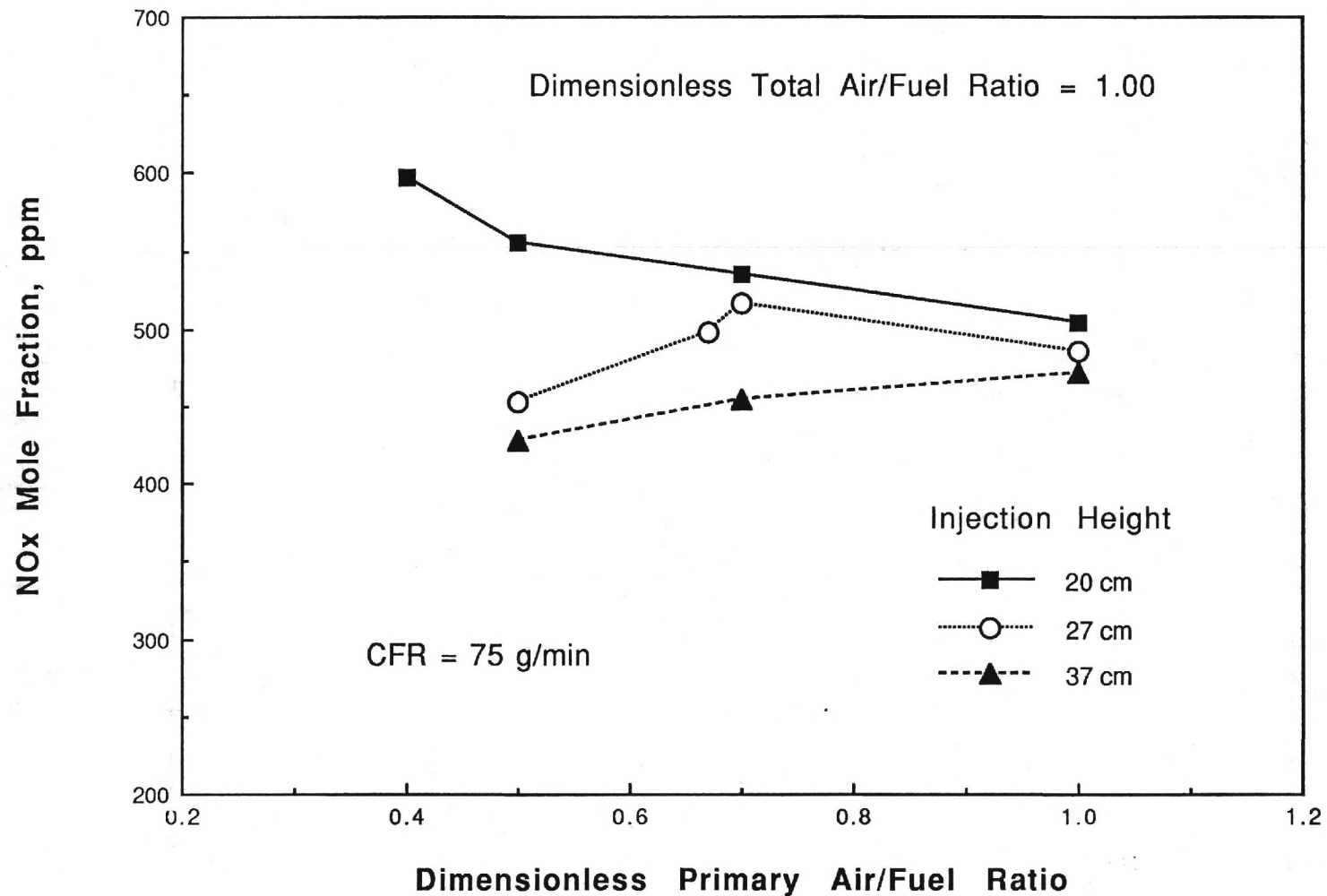


Figure 27. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on Nitrogen Oxides Emissions.

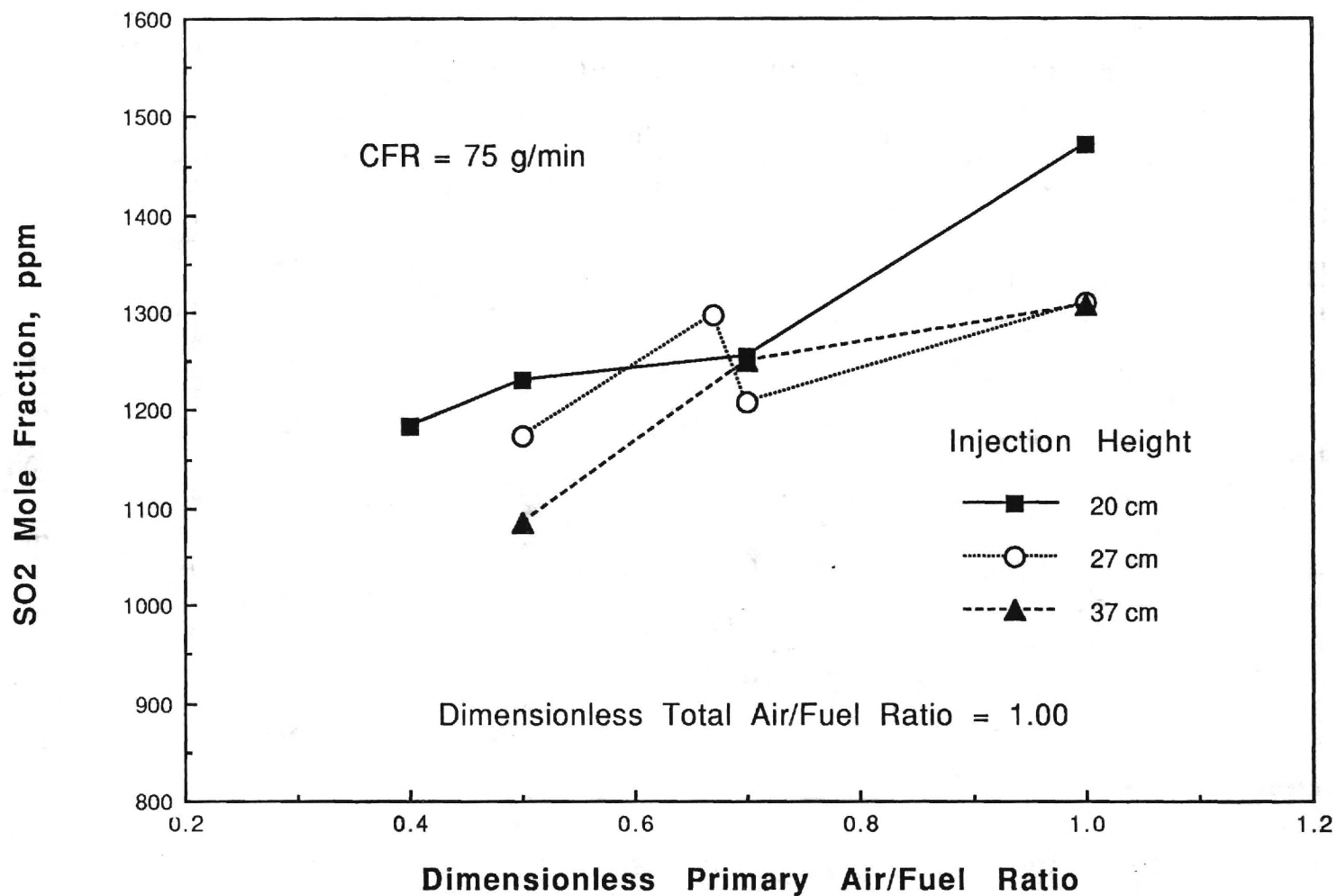


Figure 28. Effect of Dimensionless Primary Air/Fuel Ratio and Secondary Air Injection Height on Sulfur Dioxide Emissions.

The effect of air staging on the temperature distributions in the combustor downstream of the coal bed are shown in Figure 29. Here, temperature profiles are shown for secondary air injection at 37 cm above the bed for different primary air/fuel ratios. The curve for  $\alpha_1 = 1.0$  represents stoichiometric burning without air staging, where the monotonic decrease in temperature with increasing height above the coal bed is due to heat losses through the combustor walls. For the two cases with secondary air injection, the heat release in the secondary combustion zone results in higher temperatures in this region (25 - 45 cm above the bed) than those obtained without air staging. For positions higher than 75 cm above the bed, the temperatures obtained with air staging are considerably lower than those obtained without secondary air. Since the total air/fuel ratio for all three cases is the same, this temperature deficit at the combustor exit is a further indication of the incomplete combustion and resultant smaller heat release obtained with air staging under pulsating combustion conditions.

#### AIR STAGING EXPERIMENTS WITH $\alpha_t$ GREATER THAN UNITY

The second group of air staging experiments was conducted with total dimensionless air/fuel ratios greater than one. The secondary air was also injected higher above the bed (52 cm) than in the first group of air staging experiments. This injection height was chosen based on data from the earlier experiments which indicated that  $\text{NO}_x$  emissions decreased with increasing injection height (see Fig. 24). In this series, as in the previous one, the coal feed rate was 75 g/min. A total of 16 experiments was conducted in this series, each consisting of four or five segments lasting about five minutes each. In each experiment the primary dimensionless air/fuel ratio was fixed, while the amount of secondary air and hence the total dimensionless air/fuel ratio was varied stepwise from 1.1 to 1.4. Experiments were conducted for primary air/fuel ratios of 0.9, 0.8, 0.7 and 0.6. As in the previous experiments, measurements of sound

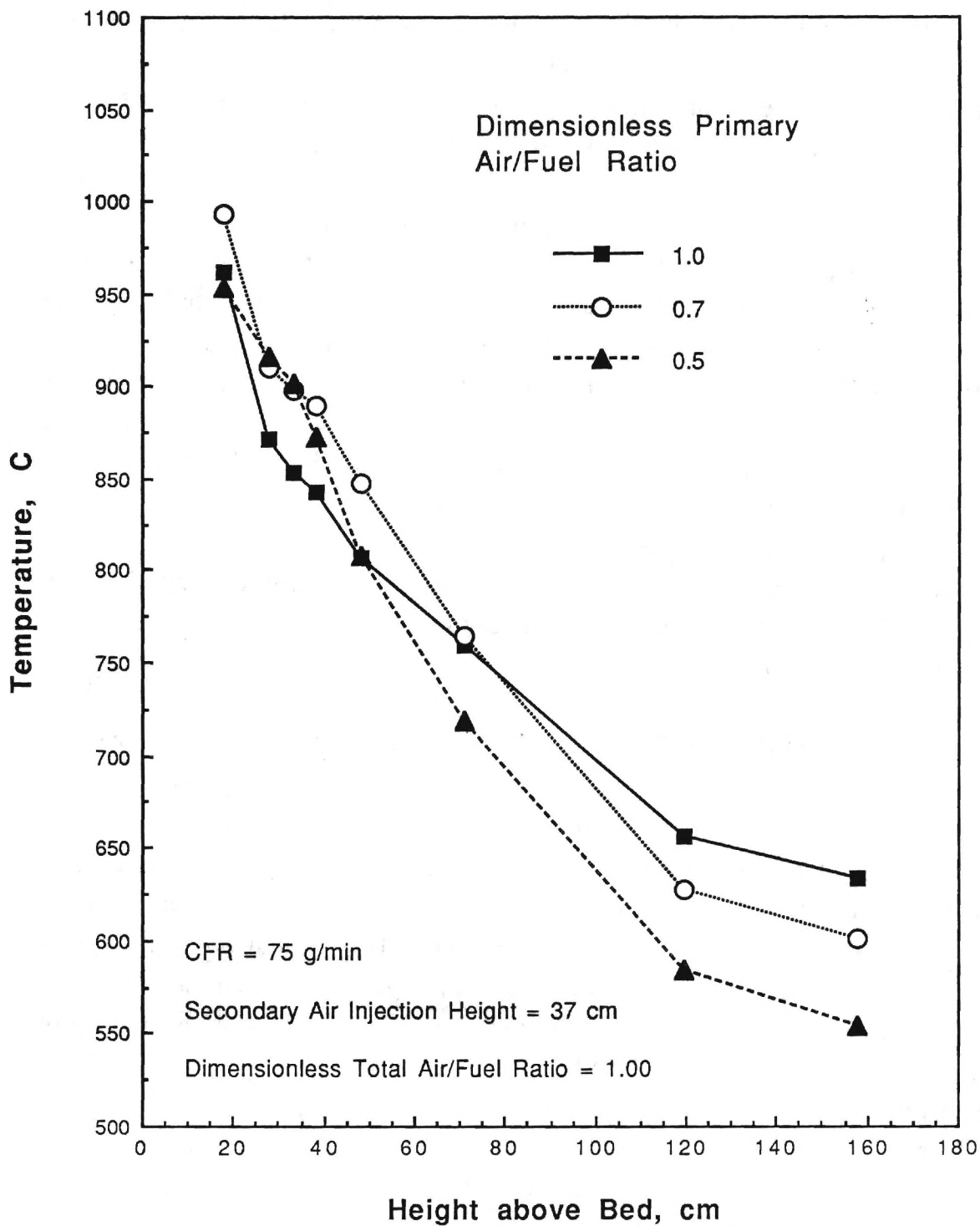


Figure 29. Effect of Air Staging on the Gas Temperature Distributions Downstream of the Coal Bed.

pressure levels, frequencies, and gas compositions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$ ) and gas temperatures were made. However the  $\text{CO}$  and  $\text{SO}_2$  data are not relevant to the issue of  $\text{NO}_x$  reduction, and they are not included in the results presented herein.

The results of the air staging experiments for  $\alpha_t > 1.0$  are summarized in Tables IV through VI and in Figures 30 through 33. The individual test data are given in Table IV for primary dimensionless air/fuel ratios of 0.9 and 0.8. Each set of values of sound pressure level (SPL), mole fractions of carbon dioxide ( $\text{CO}_2$ ), oxygen ( $\text{O}_2$ ), and nitrogen oxides ( $\text{NO}_x$ ), and the combustion efficiencies presented in Table IV are the time averages over the appropriate test segment in a single air-staging experiment. For a given primary dimensionless air/fuel ratio,  $\alpha_1$ , two to four test segments were conducted for each value of the total dimensionless air/fuel ratio,  $\alpha_t$ . The corresponding time averages for primary dimensionless air/fuel ratios of 0.7 and 0.6 are given in Table V. The  $\text{NO}_x$  emissions data has been reduced to a 0% oxygen basis using the formula:

$$\text{NO}_x (0\% \text{ O}_2) = [\text{NO}_x] / (1 - [\text{O}_2] / 0.21)$$

where

$[\text{NO}_x]$  = measured exhaust  $\text{NO}_x$  concentration in ppm

$[\text{O}_2]$  = measured  $\text{O}_2$  mole fraction in exhaust

The combustion efficiency  $\eta_c$  was calculated using the formula:

$$\eta_c = 0.217 + (0.173 [\text{CO}_2] + 0.049 [\text{CO}]) N_{td}$$

where

$[\text{CO}_2]$  = measured exhaust  $\text{CO}_2$  mole fraction

$[\text{CO}]$  = measured exhaust  $\text{CO}$  mole fraction

$N_{td}$  = total number of moles in exhaust, dry basis

Table IV. Air Staging Data for Primary Dimensionless Air/Fuel Ratios of 0.9 and 0.8 for  $\alpha_t > 1.00$ .

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	SPL (dB)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	NO <sub>x</sub> (0% O <sub>2</sub> ) (ppm)	Combustion Efficiency
0.9	1.1	158.1	16.3	2.95	420	0.99
0.9	1.1	158.9	14.8	4.77	591	0.92
0.9	1.1	159.1	14.8	3.33	497	0.92
0.9	1.1	156.1	14.5	4.90	549	0.90
0.9	1.2	158.6	13.6	6.35	642	0.92
0.9	1.2	157.6	15.3	4.19	401	1.01
0.9	1.2	156.6	14.1	5.42	480	0.94
0.9	1.2	158.5	13.5	5.15	532	0.92
0.9	1.3	156.9	13.3	6.19	439	0.96
0.9	1.3	157.2	13.5	6.11	469	0.97
0.9	1.3	158.9	13.1	5.53	505	0.95
0.9	1.4	157.3	11.7	7.65	457	0.92
0.9	1.4	158.6	NA	6.55	489	NA
0.8	1.1	155.7	15.9	2.82	341	0.97
0.8	1.1	159.4	14.7	3.34	318	0.92
0.8	1.1	157.2	14.0	4.16	316	0.88
0.8	1.2	158.7	15.2	3.38	331	1.00
0.8	1.2	155.6	13.6	4.88	350	0.92
0.8	1.2	156.3	12.5	6.07	372	0.86
0.8	1.3	158.3	14.2	4.55	348	1.01
0.8	1.3	156.1	11.4	6.92	369	0.86
0.8	1.3	156.1	11.6	7.11	377	0.87
0.8	1.4	158.3	12.7	6.34	363	0.98
0.8	1.4	155.9	9.6	8.74	389	0.81

Table V. Air Staging Data for Primary Dimensionless Air/Fuel Ratios of 0.7 and 0.6 for  $\alpha_t > 1.00$ .

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	SPL (dB)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	NO <sub>x</sub> (0% O <sub>2</sub> ) (ppm)	Combustion Efficiency
0.7	1.2	157.0	13.4	4.76	350	0.91
0.7	1.2	157.2	12.4	5.68	302	0.86
0.7	1.3	156.5	13.2	5.42	369	0.95
0.7	1.3	156.8	12.9	5.93	336	0.94
0.7	1.4	156.5	12.8	6.25	361	0.99
0.7	1.4	156.3	12.6	6.44	383	0.98
0.6	1.1	152.7	15.3	3.57	360	0.94
0.6	1.2	153.2	12.4	5.99	335	0.86
0.6	1.2	153.1	12.3	6.07	343	0.86
0.6	1.2	156.4	11.8	6.33	328	0.84
0.6	1.3	156.2	12.4	6.16	365	0.91
0.6	1.3	152.4	12.7	6.15	386	0.93
0.6	1.4	155.9	13.1	5.32	384	1.01
0.6	1.4	152.7	14.5	4.93	414	1.09

For given air staging parameters (i.e.,  $\alpha_1$  and  $\alpha_t$ ) there were considerable variations in the efficiency of the overall combustion process as reflected in the variations in the exhaust concentrations of CO<sub>2</sub> and O<sub>2</sub>. There were also significant variations in sound pressure levels and NO<sub>x</sub> concentration for tests conducted with identical air staging parameters. The variations in the measured NO<sub>x</sub> concentrations are best seen in Figure 30 where the individual time averaged test data are shown. The largest data scatter occurred for the primary dimensionless air/fuel ratio of 0.9, while the scatter was much smaller for the lower  $\alpha_1$  values. This graph readily shows that the NO<sub>x</sub> emissions were significantly reduced as the primary

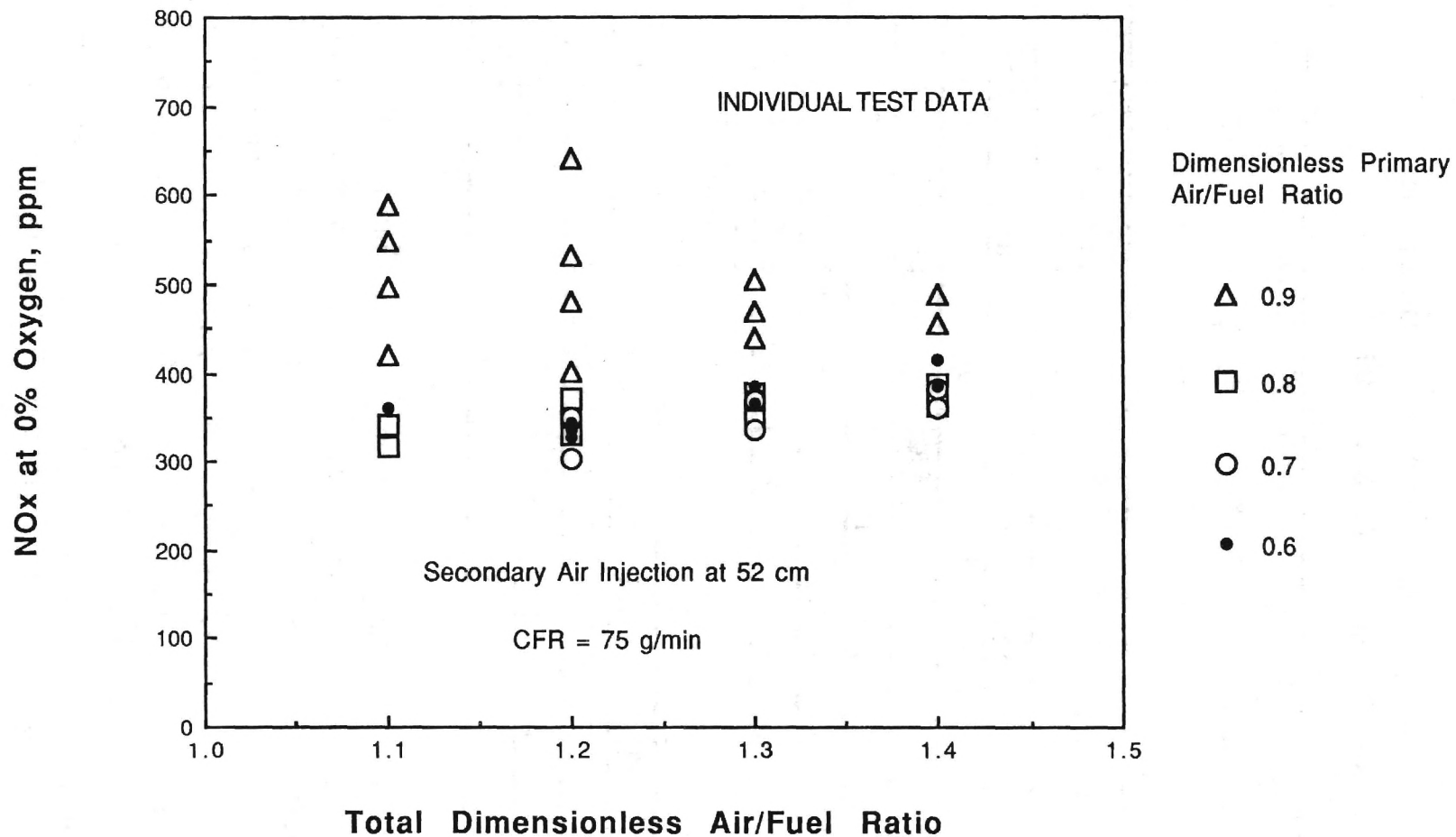


Figure 30. Individual Test Averages of Nitrogen Oxides Emissions for Air Staging Tests Showing the Effect of Total and Primary Air/Fuel Ratios.

dimensionless air/fuel ratio was decreased from 0.9 to 0.8, but only slight improvements were obtained by further decreases in the primary air/fuel ratio.

Mean values of sound pressure levels, combustion efficiencies and exhaust  $\text{NO}_x$  concentrations were also computed for each set of air staging parameters  $\alpha_1$  and  $\alpha_t$  by taking the arithmetic average of the appropriate values shown in Tables IV and V. These mean values are given in Table VI.

Table VI. Averaged Air Staging Data for Experiments with  $\alpha_t > 1.00$ .

Primary Air/Fuel Ratio $\alpha_1$	Total Air/Fuel Ratio $\alpha_t$	Sound Pressure Level (dB)	Combustion Efficiency	$\text{NO}_x$ (0% Oxygen) (ppm)
0.9	1.1	158.1	0.93	514
0.9	1.2	157.8	0.95	514
0.9	1.3	157.7	0.96	471
0.9	1.4	158.0	0.92	473
0.8	1.1	157.4	0.92	325
0.8	1.2	156.9	0.93	351
0.8	1.3	156.8	0.91	365
0.8	1.4	157.1	0.90	376
0.7	1.2	157.1	0.89	326
0.7	1.3	156.7	0.95	353
0.7	1.4	156.4	0.99	372
0.6	1.1	152.7	0.94	360
0.6	1.2	154.2	0.85	335
0.6	1.3	154.3	0.92	376
0.6	1.4	154.3	NA	399

The mean  $\text{NO}_x$  concentrations given in Table VI were plotted as a function of the total dimensionless air/fuel ratio,  $\alpha_t$ , for each value of the primary dimensionless air/fuel ratio,  $\alpha_1$ . These averaged  $\text{NO}_x$

data are shown in Figure 31 along with the baseline  $\text{NO}_x$  concentrations obtained without air/staging. For the air staging data, a linear regression curve fit is shown for each primary air/fuel ratio, while a quadratic curve fit (nonlinear regression) is shown for the baseline data. Comparison of the air-staging curves with the baseline curve reveals that air staging yielded a very significant reduction in  $\text{NO}_x$  concentrations when expressed on a 0% oxygen basis. These reductions in  $\text{NO}_x$  emissions, which were small to modest for the lowest total air/fuel ratio (1.1), increased significantly as the total air/fuel ratio was increased. Extrapolation of the linear regression lines to  $\alpha_t = 1.0$  shows that only small reductions or even increases ( $\alpha_1 = 0.9$ ) in  $\text{NO}_x$  emissions occur with air staging to final stoichiometric conditions, which agrees with the results obtained in the first group of air staging experiments. The largest reductions in  $\text{NO}_x$  occurred when going from no air staging (baseline) to air staging with a primary dimensionless air/fuel ratio of 0.9. Significant further reductions in  $\text{NO}_x$  occurred with further reduction in the primary dimensionless air/fuel ratio to 0.8, but little additional reduction in  $\text{NO}_x$  emissions was obtained with lower primary air/fuel ratios. Close examination of Figure 31 shows that the optimum primary dimensionless air/fuel ratio for  $\text{NO}_x$  reduction is about 0.7. For this case the reduction in  $\text{NO}_x$  exhaust concentration due to air staging ranged from about 48 percent at  $\alpha_t = 1.1$  to about 56 percent at  $\alpha_t = 1.4$ .

The averaged sound pressure levels from Table VI are plotted in Figure 32. For the air staging experiments with primary dimensionless air/fuel ratios of 0.7 to 0.9, sound pressure levels were generally about 2 to 4 decibels lower than those obtained without air staging (about 160 dB). This reduction in pulsation amplitude was expected since the combustion process no longer is completed at the optimum location in the Rijke tube (i. e., the point one fourth of the distance from the upstream end to the downstream end). With air staging, a significant fraction of the heat addition occurs in the region where the secondary air is injected, which is nearer to the midpoint of the tube. Even lower pulsation amplitudes,

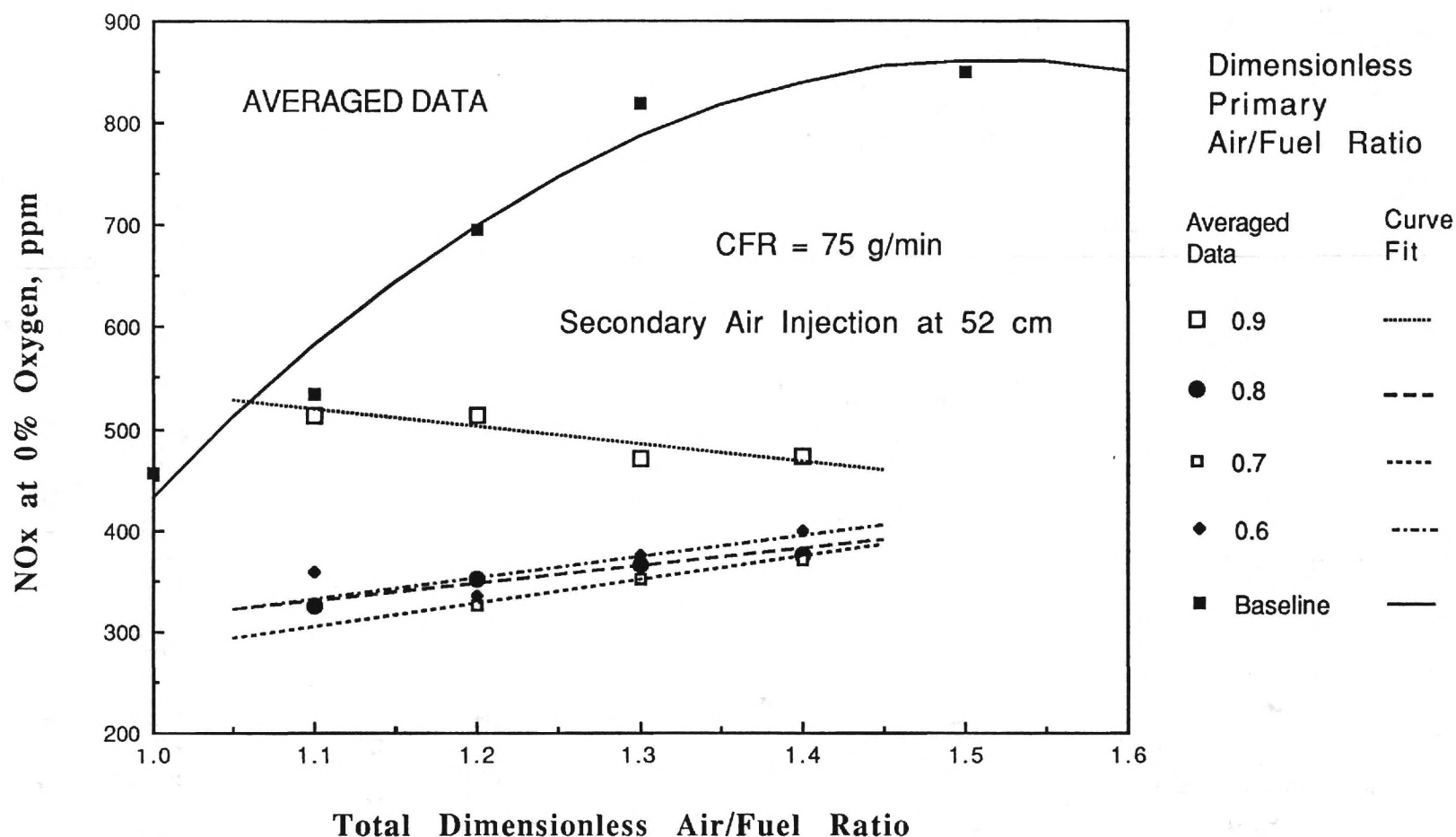


Figure 31. Comparison of Averaged Nitrogen Oxides Emissions for Air Staging Experiments with Baseline Experiments for Different Total and Primary Air/Fuel Ratios.

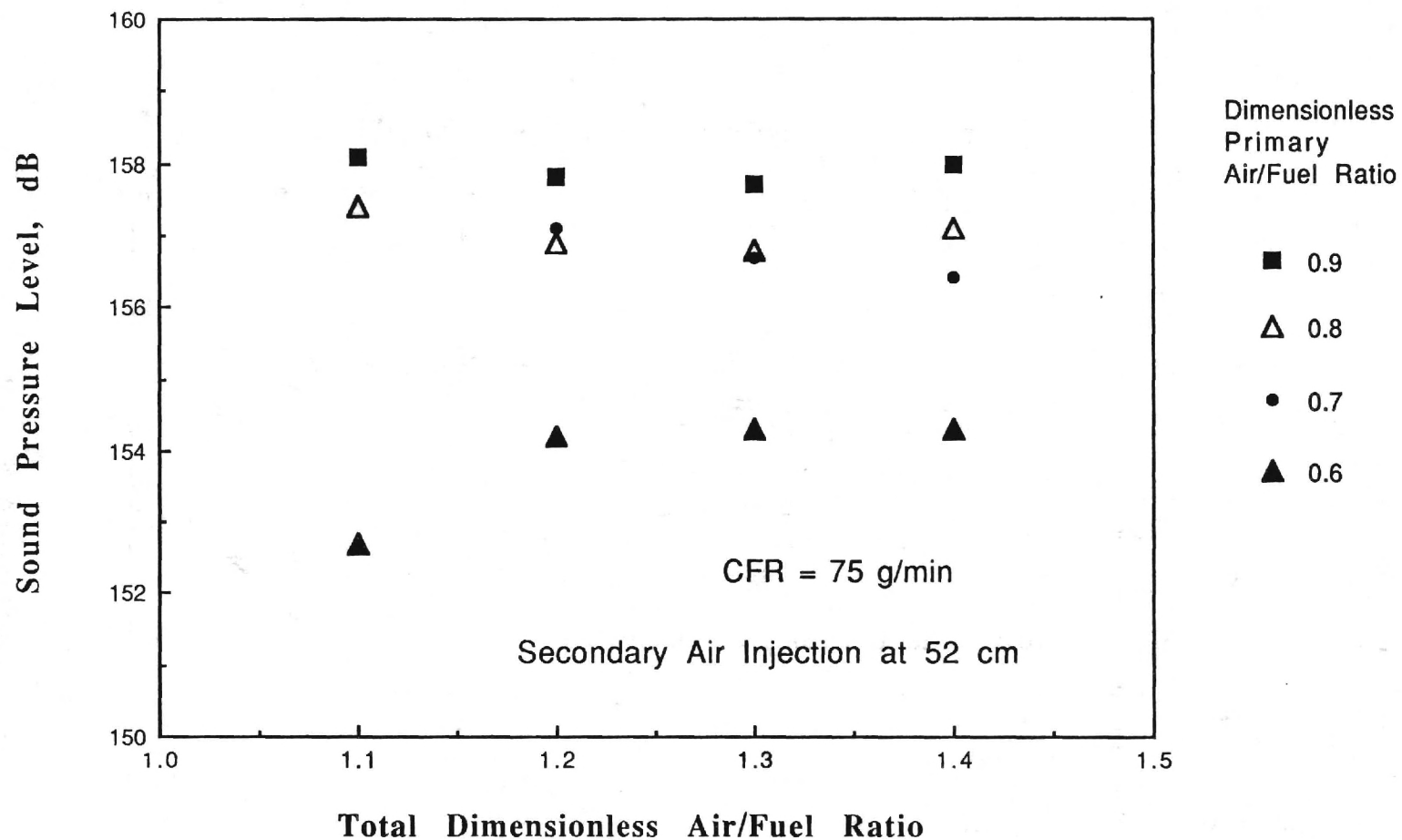


Figure 32. Effect of Total Air/Fuel Ratio and Primary Air/Fuel Ratio on Sound Pressure Levels for Air Staging Experiments.

from 6 to 7 decibels lower than baseline levels, were obtained when the primary air/fuel ratio was 0.6.

The averaged combustion efficiencies from Table VI are plotted in Figure 33. These efficiencies ranged from about 85 percent to 99 percent. Only for primary dimensionless air/fuel ratios of 0.9 and 0.8 is the combustion efficiency lower for the lower primary air/fuel ratio for all total air/fuel ratios tested. Thus the combustion efficiency is significantly influenced by factors other than the pulsation amplitude, since sound pressure levels generally decrease with decreasing primary dimensionless air/fuel ratio. One factor of considerable variability which influenced the combustion efficiency was the amount of unburned carbon in the refuse which fell through the rotating bed grid.

Gas temperatures were measured at the following eight stations above the coal bed: 7, 11, 15, 19, 23, 28, 62 and 107 cm. All of the thermocouples were positioned to measure the temperature at the axis of the combustor. Gas temperature profiles obtained during the experiments with secondary air injection at 52 cm above the bed are shown in Figures 34 and 35.

Figure 34 shows the temperature profiles for  $\alpha_1 = 0.8$  and  $\alpha_1 = 0.6$  for different dimensionless total air/fuel ratios ( $\alpha_t$ ). For  $\alpha_1 = 0.8$  (upper graph) there is little effect of total air/fuel ratio on the temperature profiles, for which the gas temperature falls rapidly from about 1100 C at 7 cm above the bed to about 700 C at about 30 cm above the bed and decreases more gradually to about 500 C at about 110 cm above the bed. For  $\alpha_1 = 0.6$  (lower graph) increasing the total air/fuel ratio from 1.2 to 1.4 increases the gas temperatures by about 100 C for all stations higher than 20 cm above the bed. This includes stations well below the secondary injection point, thus it is apparent that secondary air is being mixed with the incompletely burned gases above the bed by means of the acoustic velocity oscillations which produce reverse flow during part of each oscillation cycle. As a result of this mixing, further combustion occurs

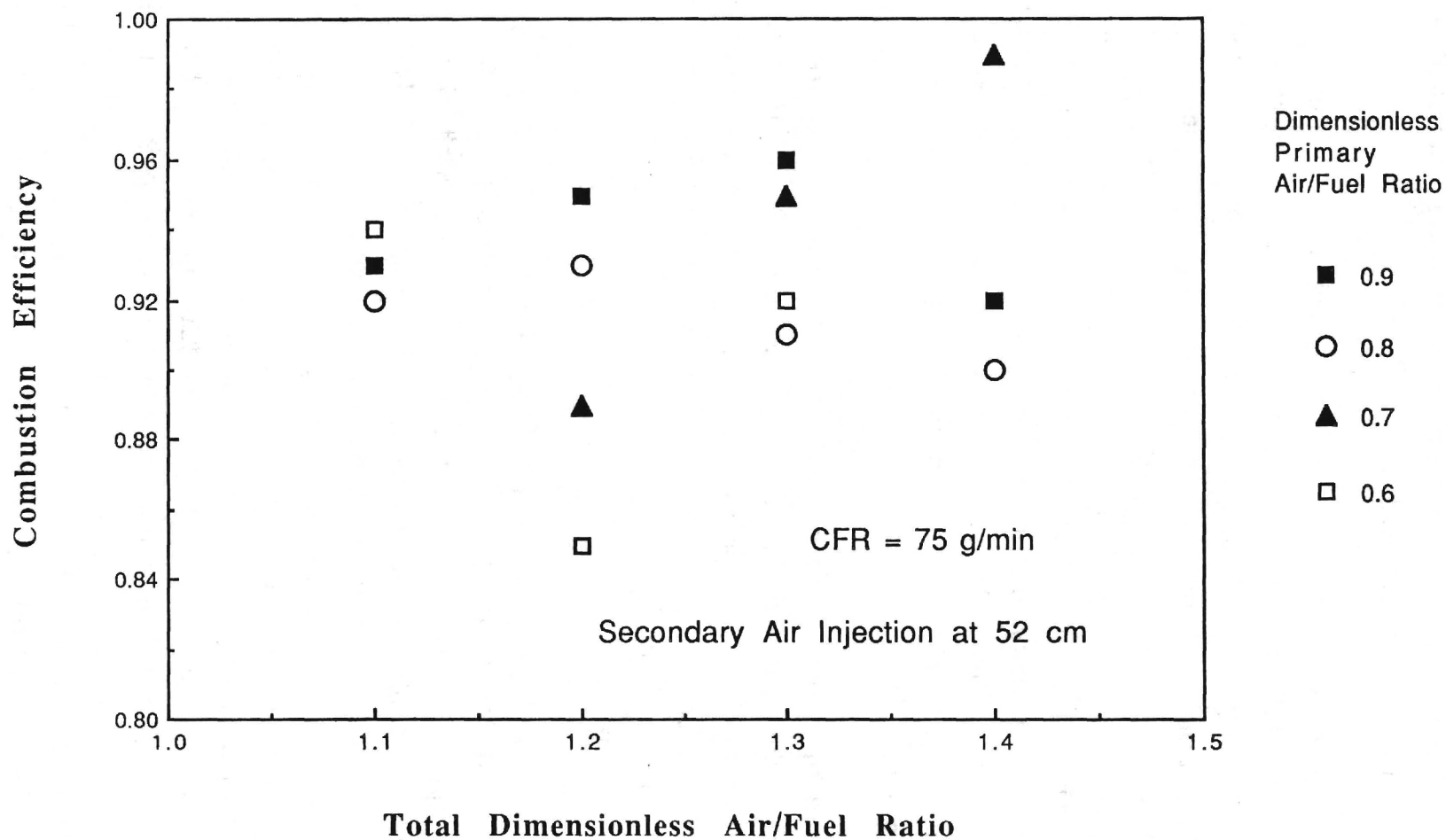


Figure 33. Combustion Efficiencies for Air Staging Experiments.

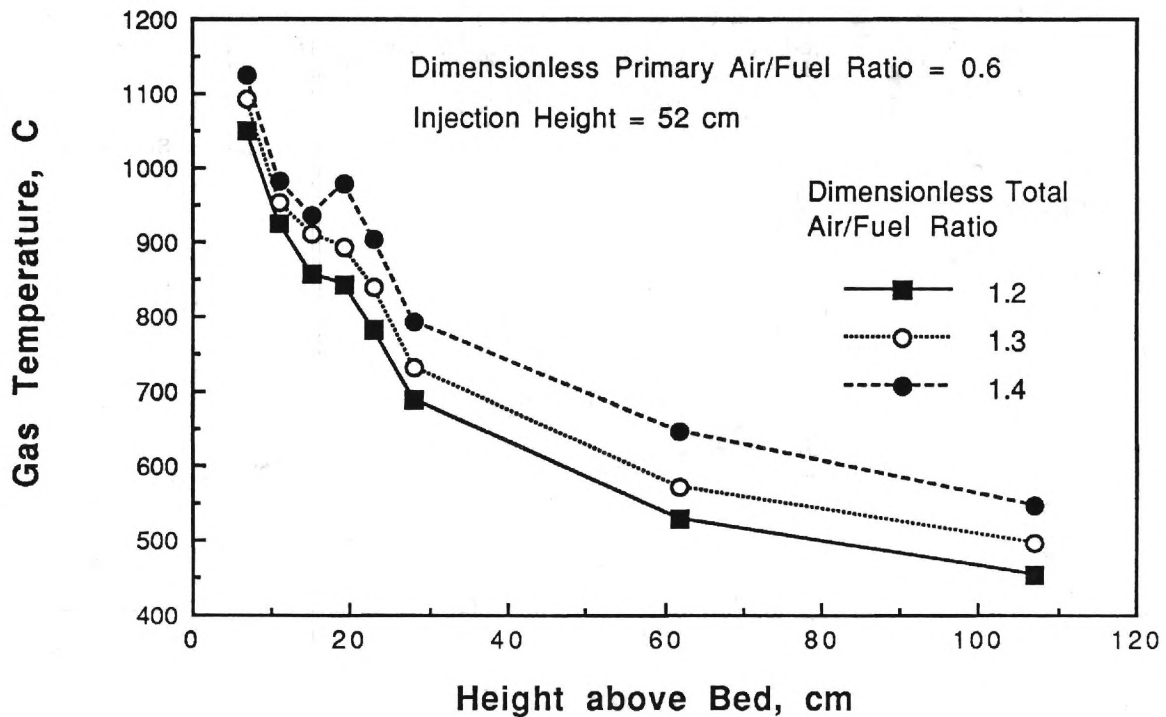
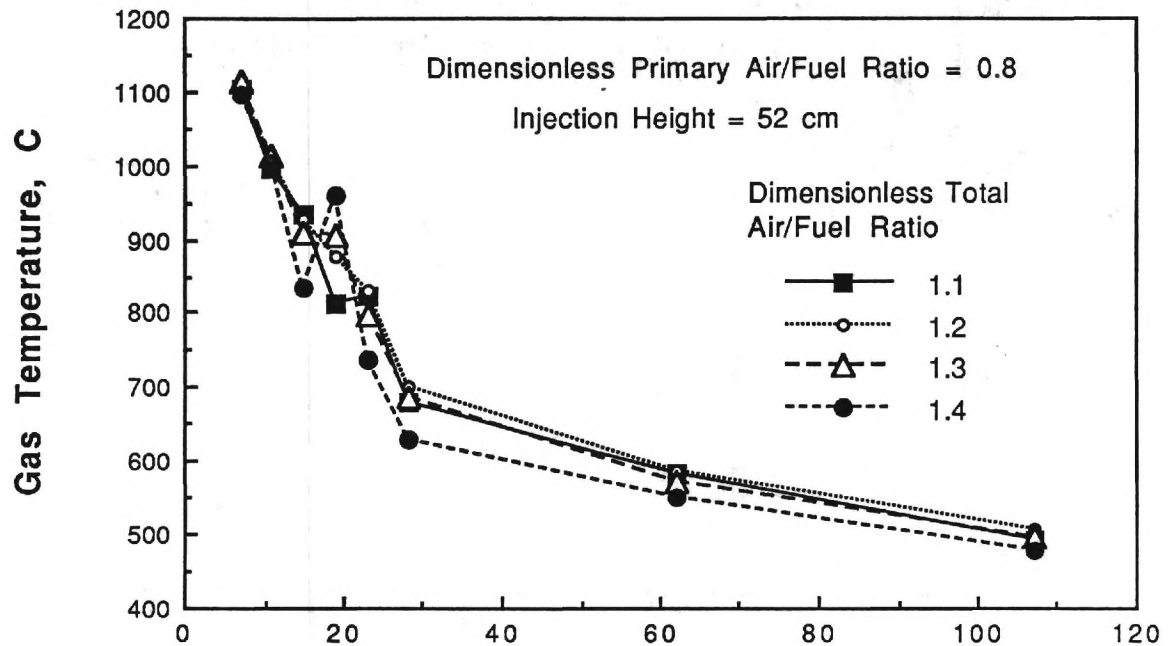


Figure 34. Gas Temperature Profiles for Experiments with Secondary Air Injection at 52 cm for Primary Air/Fuel Ratios of 0.8 and 0.6.

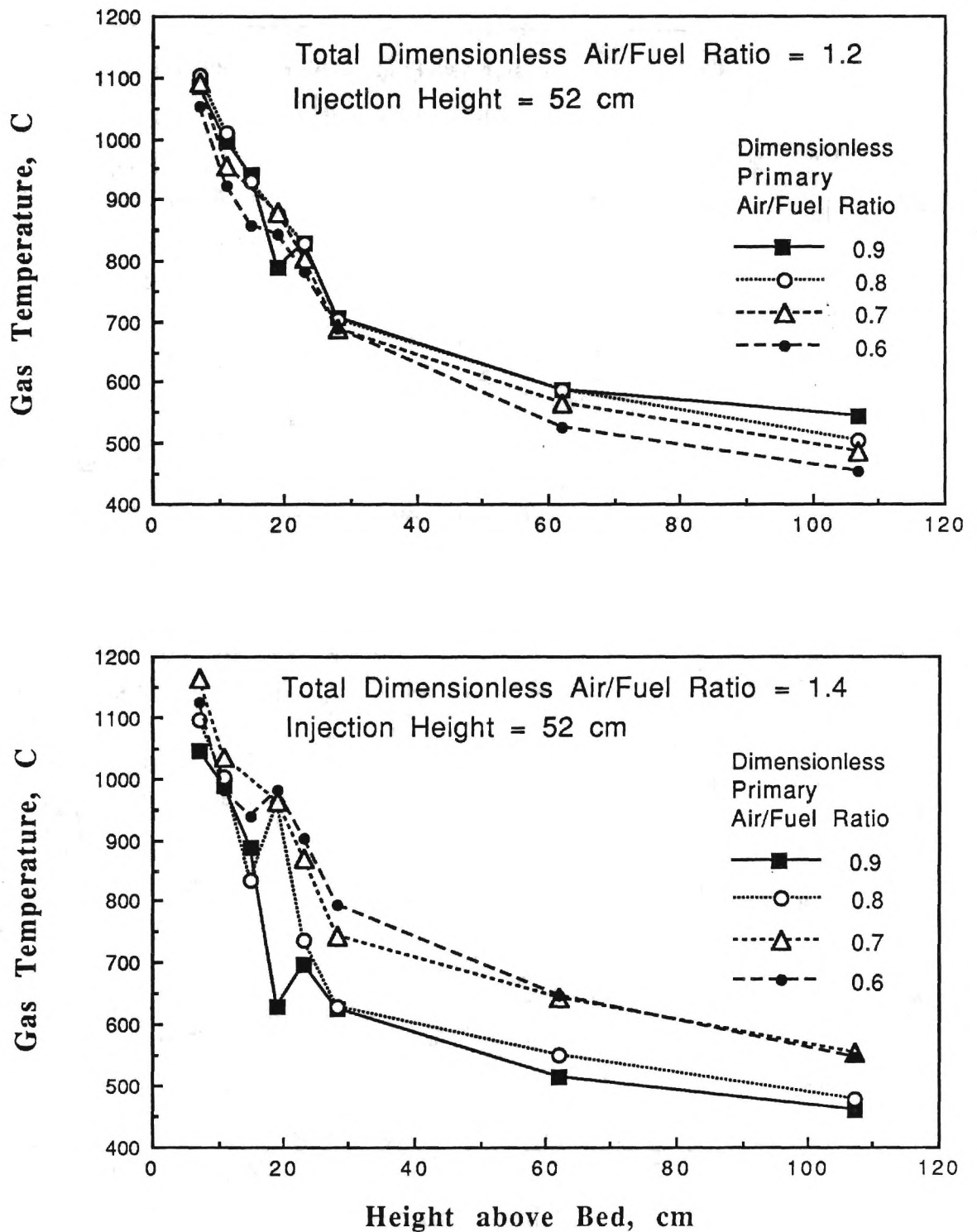


Figure 35. Gas Temperature Profiles for Experiments with Secondary Air Injection at 52 cm for Total Air/Fuel Ratios of 1.2 and 1.4.

in this region which accounts for the temperature rise. A somewhat smaller temperature rise with increasing  $\alpha_t$  was obtained for  $\alpha_1 = 0.7$  (not shown). For  $\alpha_1 = 0.9$  (not shown) there was little effect of  $\alpha_t$  on the temperature profiles for  $\alpha_t$  between 1.1 and 1.3, and a temperature decrease was obtained with further increases in  $\alpha_t$  to 1.4. For this highest primary air/fuel ratio, the amount of unburned combustible gases above the bed was small, so that the larger amounts of secondary air resulted in temperature decreases due to the dilution effect.

The temperature data can also be plotted for a fixed total dimensionless air/fuel ratio and different values of the dimensionless primary air/fuel ratio. Such plots for  $\alpha_t = 1.2$  and  $\alpha_t = 1.4$  are shown in Figure 35. For  $\alpha_t = 1.2$  (upper graph) and below, decreasing the primary air/fuel ratio results in a moderate decrease in gas temperatures at stations higher than about 40 cm above the bed, while for  $\alpha_t = 1.4$  (lower graph), decreasing the primary air/fuel ratio has the opposite effect on the gas temperatures over the same region. At the lower total air/fuel ratios, the amount of secondary air is insufficient to obtain complete combustion of the fuel (due to incomplete mixing) and temperature falls with decreasing primary air/fuel ratio. At the highest total air/fuel ratio, the secondary air is sufficient for nearly complete combustion and temperatures in the secondary combustion zone rise with decreasing primary air/fuel ratio. For  $\alpha_t = 1.3$  (not shown) there is little effect of primary air/fuel ratio on gas temperatures.

## NON-PULSATING EXPERIMENTS

A series of experiments was conducted under non-pulsating combustion conditions in order to determine the effect of pulsations on the performance of the combustor, particularly regarding  $\text{NO}_x$  and  $\text{SO}_2$  emissions. Non-pulsating operation was obtained by partially opening the viewing window at the middle of the combustor, which forced the pressure perturbation to be zero where the pressure oscillations for the fundamental acoustic mode normally have their

maximum amplitude. To reduce the air leakage through this large opening, it was covered by a piece of cloth. A total of five non-pulsating experiments were conducted. Each experimental run was divided into four or five segments of about five minutes length. Most of the experiments were conducted without air staging, but in one of the experiments secondary air was injected 20 cm above the bed.

The results of the non-pulsating experiments without air staging are shown in Table VII and in Figures 36 through 39. The data shown are time-averaged values for the appropriate test segments. In Table VII,  $T_1$  is the gas temperature measured on the axis of the combustor 18 cm above the bed. For test numbers 1-3, the coal feed rate was 75 g/min, while in test numbers 4 and 5, the coal feed rate was 40 g/min.

As shown in Table VII, there is considerable variation in the measured values from one experiment to another for the same dimensionless air/fuel ratio. This is due largely to the varying amounts of partially burned coal which fell through and around the periphery of the coal bed during the non-pulsating tests. Thus the effective air/fuel ratios varied considerably among each group of test segments with the same nominal dimensionless air/fuel ratio. Furthermore, the effective air/fuel ratios were always higher than the nominal values shown in Table VII. For this reason it was found to be more meaningful to plot the measured values of  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$  and  $\text{SO}_2$  concentrations as a function of the  $\text{O}_2$  concentration rather than the air/fuel ratio. The amount of residual oxygen remaining in the exhaust gases is a function of the both the nominal air/fuel ratio and the combustion efficiency. Plots of the concentrations of these four species as a function of residual oxygen concentration are shown in Figures 36 through 39.

The data shown in Figure 36 reveals that measured carbon dioxide concentrations for both pulsating and non-pulsating combustion are nearly linearly related to the residual oxygen concentration. For non-pulsating combustion,  $\text{CO}_2$  concentrations

ranged from about 5 percent to about 11 percent, while the corresponding residual oxygen concentrations varied from about 15 percent to about 7 percent. Some of the scatter in the non-pulsating data results from differences in the dimensionless air/fuel ratios and coal feed rates for the different experiments. For the pulsating experiments, air/fuel ratios ranged from 0.6 to 1.5. The CO<sub>2</sub> concentrations for pulsating combustion were much higher with correspondingly lower residual O<sub>2</sub> concentrations. The pulsating experiments with the largest concentrations of residual oxygen corresponded to those with the largest amounts of excess air. These results show that the combustion efficiency is much lower under non-pulsating conditions, indicating incomplete combustion of the coal.

Table VII. Exhaust Gas Compositions and Above-Bed Temperatures for Non-Pulsating Tests Without Air Staging.

Test Number	$\alpha$	CO <sub>2</sub> (%)	CO (%)	NO <sub>x</sub> (ppm)	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)	T <sub>1</sub> (C)
1	0.5	10.82	0.80	278	1412	6.50	994
2	0.5	10.10	1.01	199	1462	7.30	1082
3	0.5	5.15	0.35	114	831	14.77	1005
4	0.5	7.96	0.20	143	967	11.85	893
5	0.5	9.58	0.29	170	954	11.45	892
2	0.7	9.48	0.32	242	1064	8.76	1027
3	0.7	5.99	0.33	136	801	13.83	1034
4	0.7	6.83	0.10	125	1041	13.38	862
5	0.7	9.27	0.18	193	873	11.86	892
3	1.0	6.44	0.18	177	745	13.64	982
4	1.0	6.91	0.27	164	996	14.16	853
5	1.0	6.56	0.14	212	737	12.98	854
4	1.1	6.25	0.07	143	1043	15.15	860
5	1.1	NA	0.10	220	770	12.71	899

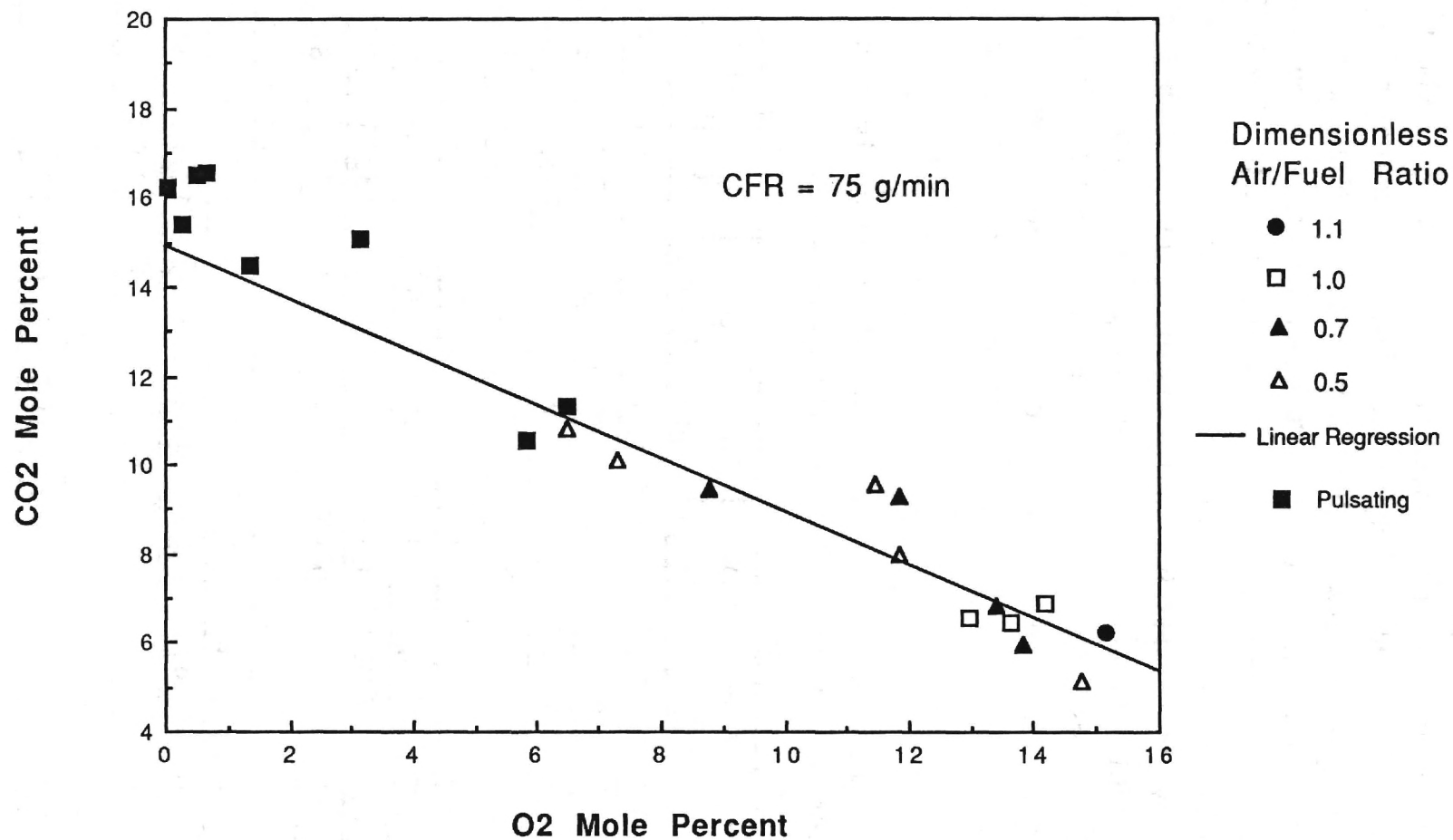


Figure 36. Comparison of Exhaust Carbon Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

The carbon monoxide concentrations measured under non-pulsating combustion conditions are shown in Figure 37. Although there is considerable scatter in the CO data, there is a definite trend of decreasing CO concentration with increasing residual oxygen for the non-pulsating experiments. Similar results were obtained for pulsating combustion, but the corresponding residual oxygen levels were much lower due to the higher combustion efficiency. The decrease in CO concentration with increasing residual O<sub>2</sub> levels reflects the gas phase oxidation of CO to CO<sub>2</sub> in the region above the coal bed when ample oxygen is present.

The nitrogen oxides emissions measured under non-pulsating combustion conditions are shown in Figure 38. These data follow a definite trend of decreasing NO<sub>x</sub> concentration with increasing O<sub>2</sub> concentration. Furthermore if a linear curve fit for the non-pulsating data is extended to very low residual oxygen levels, it agrees well with the pulsating combustion data for air/fuel ratios between 0.6 and 1.1, which is approximately the same range of  $\alpha$  used in the non-pulsating experiments. For this range in  $\alpha$  the residual oxygen levels are a good measure of combustion efficiency, since little or no excess air is present. It thus appears that as the combustion efficiency increases, as evidenced by the decrease in residual oxygen, the production of nitrogen oxides from fuel-bound nitrogen increases.

The non-pulsating data presented in Figure 38 also show a significant increase in NO<sub>x</sub> production with increasing primary air/fuel ratio. For non-pulsating combustion under stoichiometric conditions and large residual O<sub>2</sub> levels (i.e., low combustion efficiency), NO<sub>x</sub> concentrations averaged about 180 ppm, which decreased to about 115 ppm at an air/fuel ratio of about 0.5. The pulsating data for air/fuel ratios above 1.1 also exhibit this trend of increasing NO<sub>x</sub> emissions with increases in excess air (Fig. 21). These results are consistent with the hypothesis that most of the NO<sub>x</sub> is produced from fuel nitrogen and the amount produced is dependent on the availability of oxygen in the primary combustion zone. The

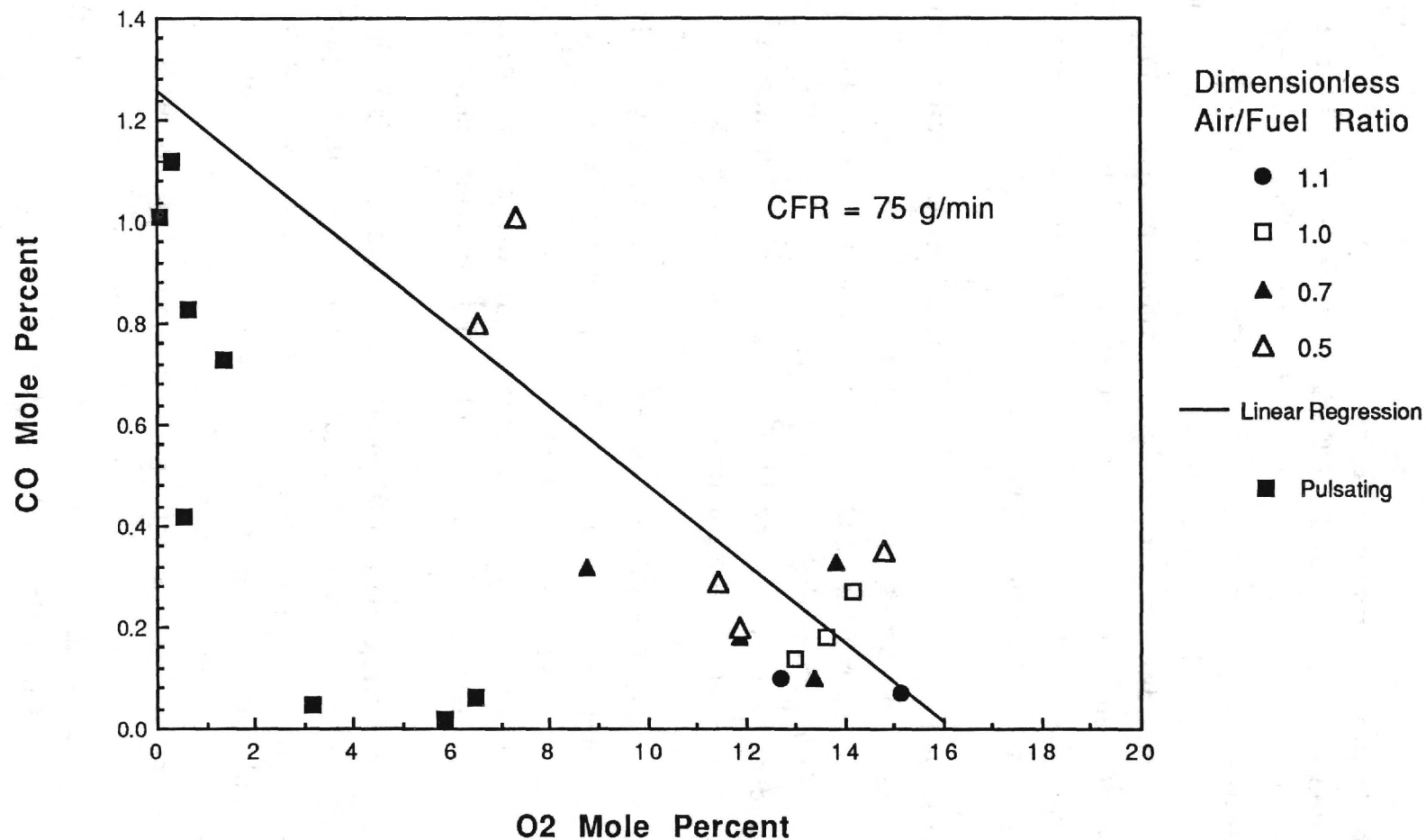


Figure 37. Comparison of Exhaust Carbon Monoxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Pulse Combustor.

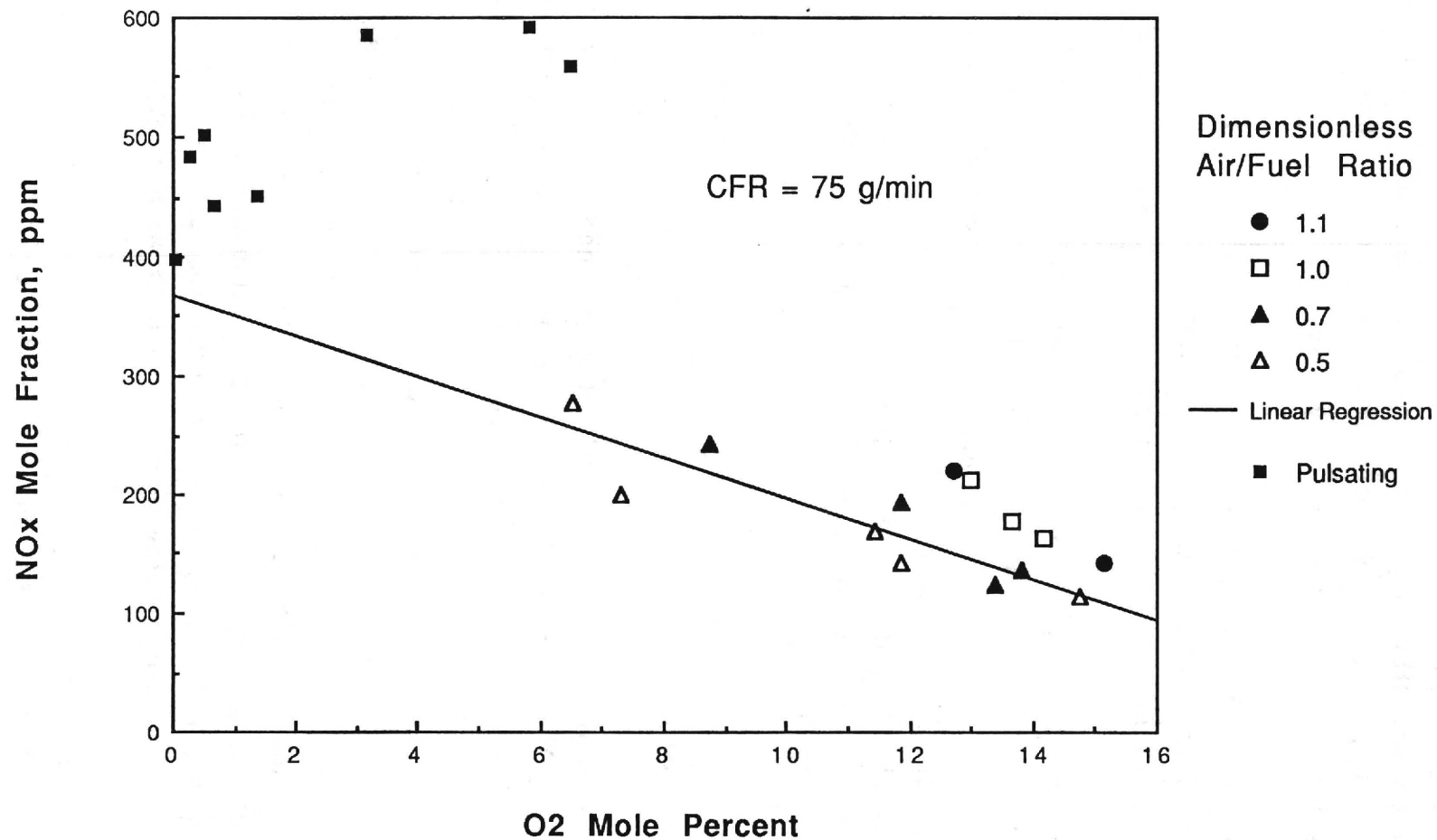


Figure 38. Comparison of Exhaust Nitrogen Oxides Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

$\text{NO}_x$  concentrations under non-pulsating combustion at high residual  $\text{O}_2$  (low combustion efficiency) were less than half (stoichiometric) to a fourth ( $\alpha = 0.5$ ) of those produced under pulsating conditions with very low residual  $\text{O}_2$  (high combustion efficiency).

Figure 39 shows the exhaust gas sulfur dioxide concentrations measured in both non-pulsating and pulsating experiments as a function of residual oxygen concentration. For substoichiometric burning in the primary combustion zone, there is a pronounced trend of decreasing  $\text{SO}_2$  emissions with increasing residual  $\text{O}_2$  concentrations (decreasing combustion efficiency). For the non-pulsating experiments under stoichiometric and excess air conditions, the scatter in the data is large, but the  $\text{SO}_2$  emissions appear to be somewhat larger than in the corresponding substoichiometric tests. The  $\text{SO}_2$  data for the pulsating tests, which follow closely a straight line curve fit, fall below the extension of the linear curve fit for the substoichiometric non-pulsating data. This is due partially to the fact that the largest  $\text{SO}_2$  values shown in Figure 39 represent nearly complete conversion of the sulfur in the coal to sulfur dioxide.

For test number 3 in Table VII, two segments were run with air staging at 20 cm above the bed under non-pulsating combustion conditions. The first segment was conducted at a primary dimensionless air/fuel ratio of 0.7, while the second segment was conducted at  $\alpha_1 = 0.5$ . The results of these experiments showed that carbon dioxide and residual oxygen levels in the exhaust were not significantly affected by air staging under non-pulsating conditions. On the other hand carbon monoxide levels were drastically reduced by air staging, indicating that some of the combustion efficiency was recovered by nearly complete combustion of the CO formed in the primary combustion zone. However the CO apparently was only a small fraction of the coal which did not burn in the primary zone. It is suspected that most of the incompletely burned material under non-pulsating conditions was fixed carbon in the coal which was lost with the ash which fell through the bed. For non-pulsating experiments with air staging, the  $\text{NO}_x$  emissions were increased. For

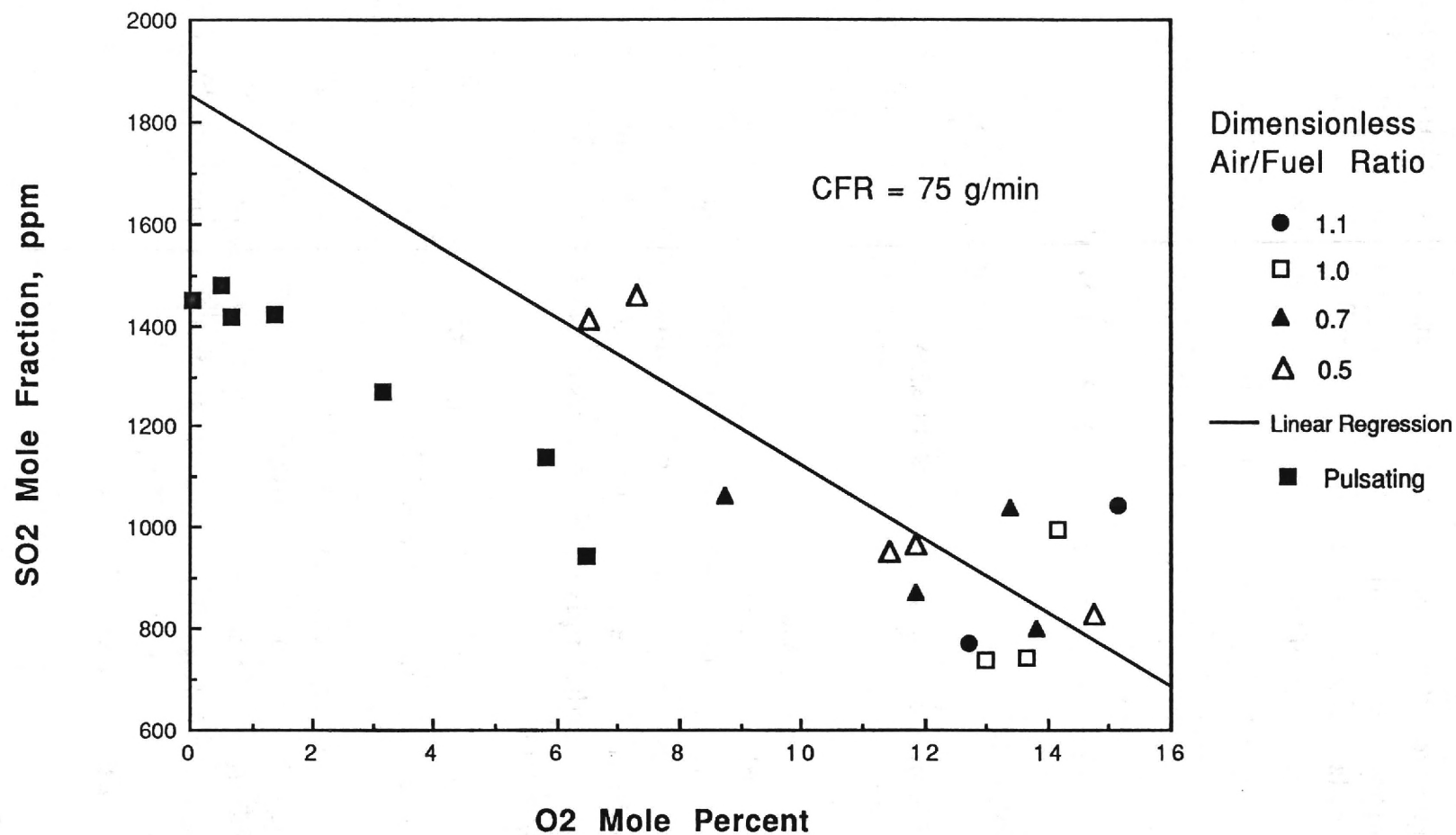


Figure 39. Comparison of Exhaust Sulfur Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

example, at  $\alpha = 0.7$ , air staging increased the  $\text{NO}_x$  concentration from 135 ppm to 205 ppm, which was larger than that produced under stoichiometric conditions in the primary zone without air staging. A similar result was obtained for  $\alpha = 0.5$ . Since this increase occurred in the secondary combustion zone where fuel-bound nitrogen is not expected to be present, it was probably due to thermal  $\text{NO}_x$  production.

## SORBENT ADDITION EXPERIMENTS

### SORBENT MATERIALS

Two dolomitic limestone materials were obtained for use as sulfur capturing agents. Both are commercially available agricultural liming products used for reducing the acidity of soils. One of the materials is in a pelletized form with particle sizes between about 0.5 and 2 mm, while the other material is in a finely pulverized form with most of the particle sizes between 0.1 mm and 1.0 mm. The mass median diameter of the pulverized limestone is 0.4 mm. The pelletized dolomitic limestone contains about 24% calcium and 8% magnesium, while the pulverized material consists of 24% calcium and 6% magnesium.

The pelletized material is too coarse to pass through the auger feed and air entrainment system. This material is more suitable for mixing with the coal and introducing it into the combustor along with the coal using the coal feed system. On the other hand, the pulverized limestone was found to be unsuitable for directly mixing with the coal. Because the limestone particles are much smaller than the coal particles, they tend to settle to the bottom of the hopper by falling through the spaces between the coal particles. Thus uniform delivery of the limestone at a fixed Ca/S ratio is impossible by this method.

## EXPERIMENTS WITH SORBENT INTRODUCED INTO COAL FEED SYSTEM

The first series of experiments with pulverized dolomitic limestone addition were conducted before the modifications of the air entrainment system were completed. The limestone auger was temporarily arranged to feed the limestone directly into the coal delivery tube. Thus the limestone and coal were fed together directly onto the coal bed grid during this series of experiments.

Each of these experimental runs was divided into two to five segments. In the first segment of a run, the combustor was operated in the pulsating mode for several minutes without sorbent addition. In subsequent run segments, dolomitic limestone was added at rates corresponding to Ca/S mole ratios ranging from 2.4 to 4.2. The coal feed rate was 75 g/min for all of these experiments. In most of the run segments, the dimensionless primary air/fuel ratio was 1.0 with no secondary air injection (air staging). In the remaining run segments the primary air/fuel ratio ranged from 1.1 to 1.6, again without air staging. The gas sampling and analysis system was used to determine sulfur dioxide concentrations in the exhaust gases. The results were reduced to a 0% oxygen basis in all cases.

The results of the these limestone addition experiments are shown in Figures 40 and 41. In Figure 40, sulfur dioxide concentrations are shown for all run segments with dimensionless air/fuel ratios of 1.0 and 1.2. The SO<sub>2</sub> concentrations obtained with sorbent addition can be compared with those obtained without sorbent addition (Ca/S = 0). For the cases with  $\alpha = 1.0$ , there is no evidence in the data for significant SO<sub>2</sub> reduction when the pulverized dolomitic limestone was added. For the cases with  $\alpha = 1.2$ , there appears to be a reduction of about 20% in SO<sub>2</sub> emissions when compared with the  $\alpha = 1.0$  case. In Figure 41, the effect of primary air/fuel ratio upon SO<sub>2</sub> concentrations are shown for a Ca/S mole ratio of 4.2. Here the individual data are plotted for

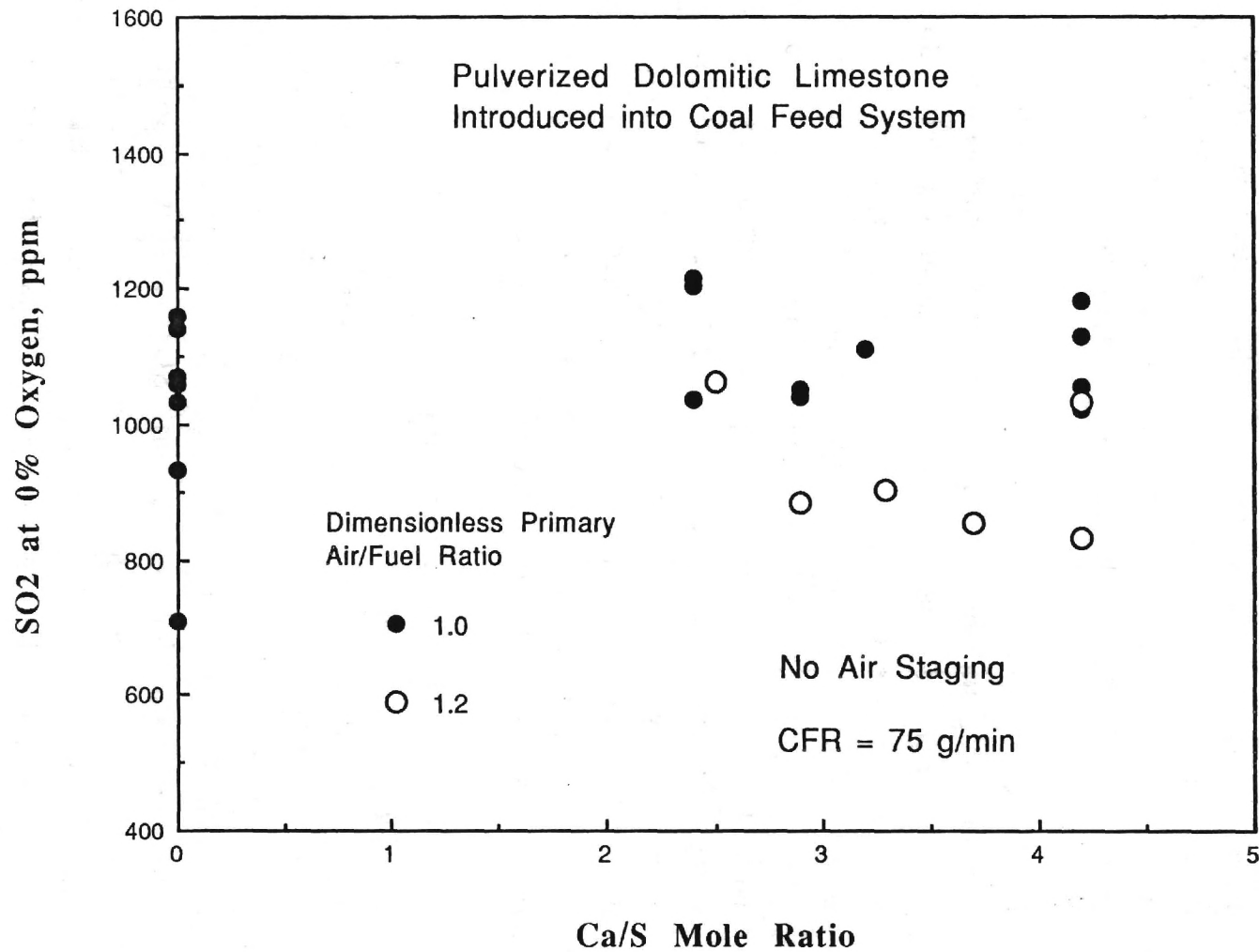


Figure 40. Effect of Ca/S Ratio on Sulfur Dioxide Emissions for Experiments with Sorbent Introduced into Coal Feed System.

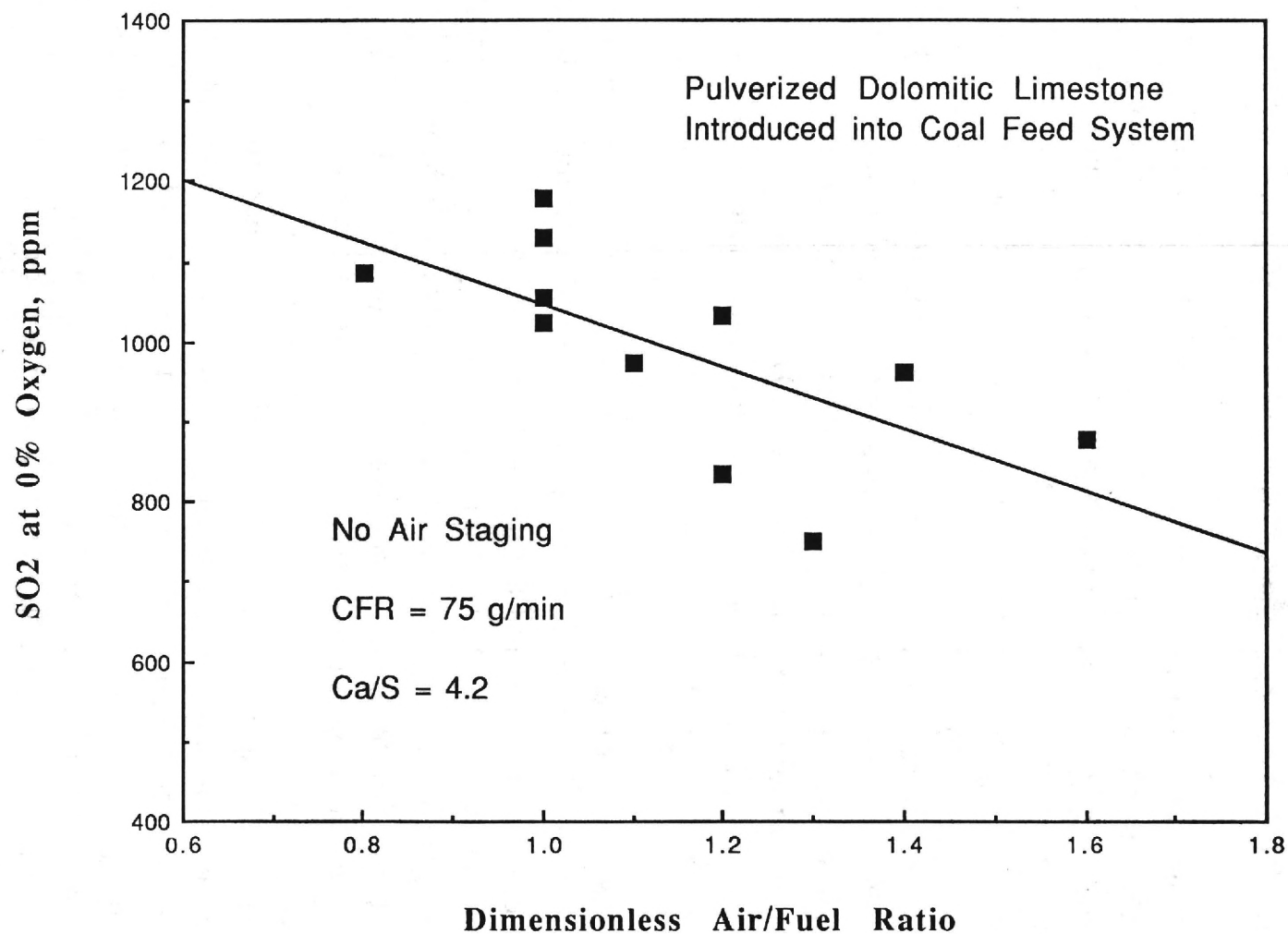


Figure 41. Effect of Air/Fuel Ratio on Sulfur Dioxide Emissions for Experiments with Sorbent Introduced into Coal Feed System.

all of these run segments along with a linear regression curve fit. This shows a definite trend of decreasing  $\text{SO}_2$  emissions when the dimensionless air/fuel ratio is increased. This result can be explained by the fact that some residual oxygen is needed in order to complete the sulfur capture process; that is, to convert the  $\text{SO}_2$  into  $\text{CaSO}_4$ .

Three additional experiments in this series were conducted, where the limestone was injected into the combustor using the air entrainment system. Each experiment was divided into three run segments, with the first segment being conducted without limestone addition. In the other run segments, limestone was added with Ca/S ratios ranging from 3.6 to 8.0. In the first two experiments the primary air/fuel ratio was 1.0, while a small amount of secondary air was needed for injection of the limestone. In the third experiment, the primary air/fuel ratio was 0.8. The coal feed rate was 75 g/min for all of the experiments. Measured  $\text{SO}_2$  concentrations indicated that little or no reduction in  $\text{SO}_2$  occurred as a result of the limestone injection even at the highest Ca/S ratio used.

There are three factors that are probably involved in the failure of the limestone addition to result in significant reduction in sulfur dioxide in this initial series of experiments: residence time, oxygen availability, and reaction temperature. When the limestone was introduced through the coal delivery tube or through the air entrainment system, the larger limestone particles fell to the coal bed where the temperature was too high for effective sulfur dioxide capture, while the smallest particles were rapidly carried out with the flow of the exhaust gases. For adequate residence time for sulfur dioxide removal, the limestone particles should be of an intermediate size so that they neither fall to the bed nor are rapidly elutriated. Also the primary combustion zone should be provided with excess air to provide adequate residual oxygen needed for sulfur dioxide removal. Finally a means of temperature control in the region immediately above the bed is needed in order to maintain the gas temperature in the optimum range for sulfur dioxide capture.

## EXPERIMENTAL RESULTS WITH PULVERIZED DOLOMITIC LIMESTONE

A more extensive series of experiments was conducted with modifications in the pulverized limestone addition procedure and operating parameters to determine if significant reductions in sulfur dioxide emissions can be obtained in the Rijke combustor. One of the modifications was the installation of a water cooled coil extending from about 5 cm below the limestone injector to about 15 cm above the injector. Some of these experiments were conducted with excess air in the primary combustion zone in order to provide adequate oxygen for sulfur dioxide removal. Finally, for some of the experiments, the limestone was further pulverized to reduce the size of the larger particles and sieved to remove the smaller particles in order to obtain particles of about 0.04 mm in diameter.

A total of 13 experiments were conducted in this series. Each experiment was divided into two to four segments. In the first segment, the combustor was operated in the pulsating mode for several minutes without sorbent addition. In subsequent segments, pulverized dolomitic limestone was introduced using the sorbent entrainment/injection system at rates corresponding to Ca/S mole ratios ranging from 1.8 to 8.0. The coal feed rate was 75 g/min for all of the experiments. In these experiments, the dimensionless primary air/fuel ratio was 1.0 or 1.1 with small amounts of secondary air injection (air staging) needed to deliver the sorbent material. Total dimensionless air/fuel ratios ranged from 1.05 to 1.30. Experiments were conducted at sorbent injection heights of 15 cm and 23 cm above the coal bed.

The gas sampling and analysis system was used to determine carbon dioxide, oxygen, and sulfur dioxide concentrations in the exhaust gases for all of these experiments. The measured sulfur dioxide concentrations were first corrected by subtracting a background reading to account for residual SO<sub>2</sub> in the sampling lines and the interfering effects of moisture. The corrected SO<sub>2</sub> concentrations were reduced to a 0% oxygen basis in all cases. In

addition, sound pressure levels and gas temperatures were measured for all of these experiments. The gas temperatures were obtained at heights of 10, 15, 20, 25, 30, 36, 157, and 272 cm above the coal bed.

Real time measurements of the exhaust concentrations of sulfur dioxide, carbon dioxide, and residual oxygen, and measured sound pressure levels are shown in Figures 42 through 44 for an experiment with sorbent injection at 23 cm above the bed. During the first nine minutes of this experiment, the combustor was operated in pulsating mode without sorbent injection ( $\text{Ca/S} = 0$ ). The pulverized dolomitic limestone was then introduced through the air entrainment system at a  $\text{Ca/S}$  ratio of 3.3 for the remainder of the experiment. Figure 42 shows the sulfur dioxide concentrations as a function of time during this experiment. The  $\text{SO}_2$  concentrations fluctuated about a mean value of about 860 ppm without sorbent addition. When the sorbent was introduced, exhaust  $\text{SO}_2$  concentrations decreased steadily over the next seven minutes, reaching a steady state level of about 300 ppm during the last six minutes of the run. This represents about a 65 percent reduction in exhaust  $\text{SO}_2$  concentration as a result of the limestone addition. The effect of limestone addition on the exhaust carbon dioxide and oxygen concentrations is shown in Figure 43. Although there appears to be a slight decrease in  $\text{CO}_2$  and a corresponding increase in  $\text{O}_2$  levels near the end of the experimental run, indicating a decrease in combustion efficiency, it does not appear to be associated with the sorbent injection process which began about ten minutes earlier. Measured sound pressure levels for this experiment are shown in Figure 44. Here the pulsation amplitude is not affected by the sorbent injection process, remaining constant at about 158 dB for most of the experimental run. The decrease in pulsation amplitude during the last four minutes of the run probably accounts for the decreased combustion efficiency noted above.

The results of the experiments with pulverized dolomitic limestone injection are summarized in Tables VIII and IX. Table VIII gives time averaged values of exhaust  $\text{SO}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$  concentrations,

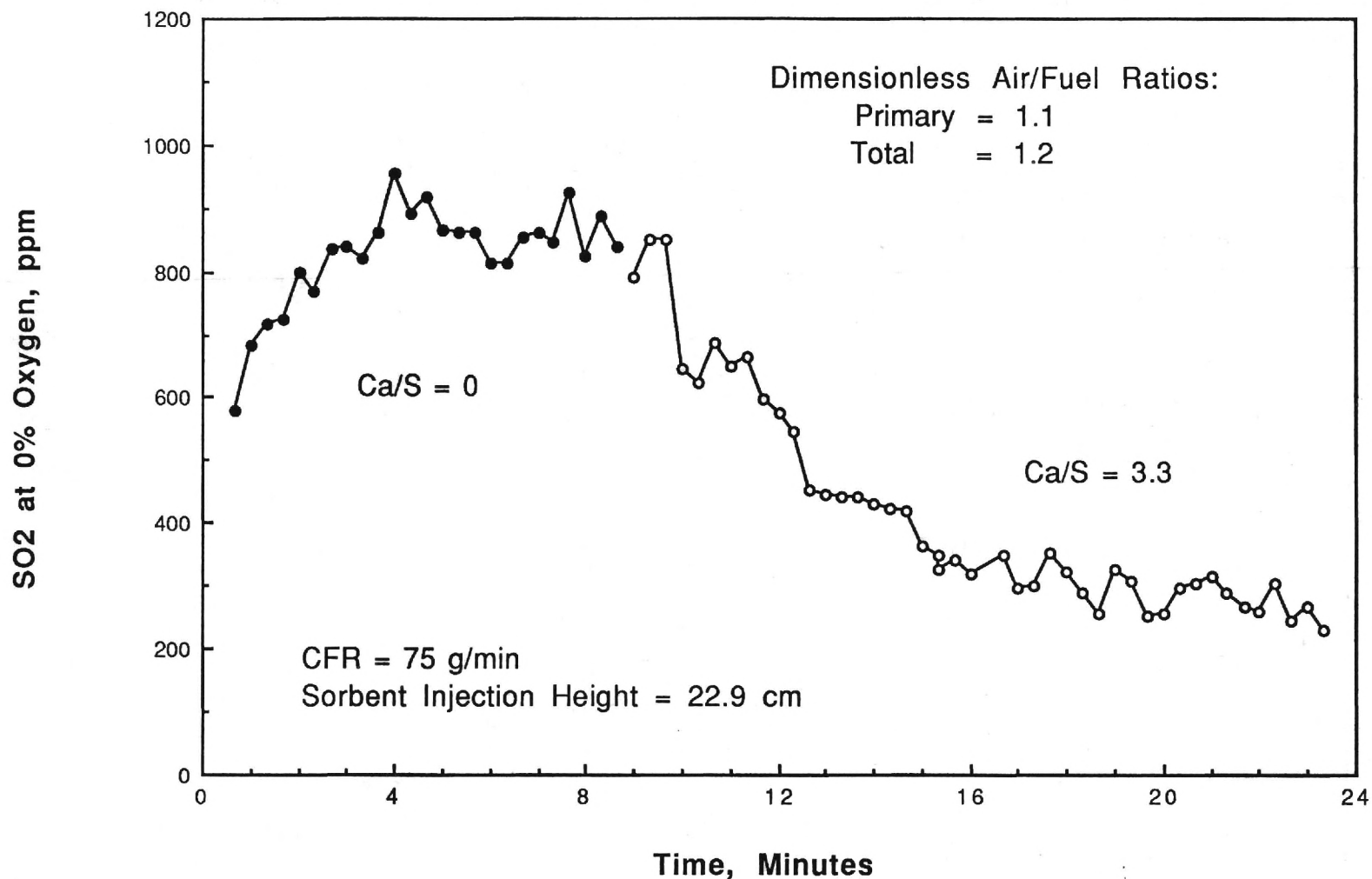


Figure 42. Real Time Sulfur Dioxide Concentrations for a Typical Experiment with Pulverized Dolomitic Limestone Injection Above Bed.

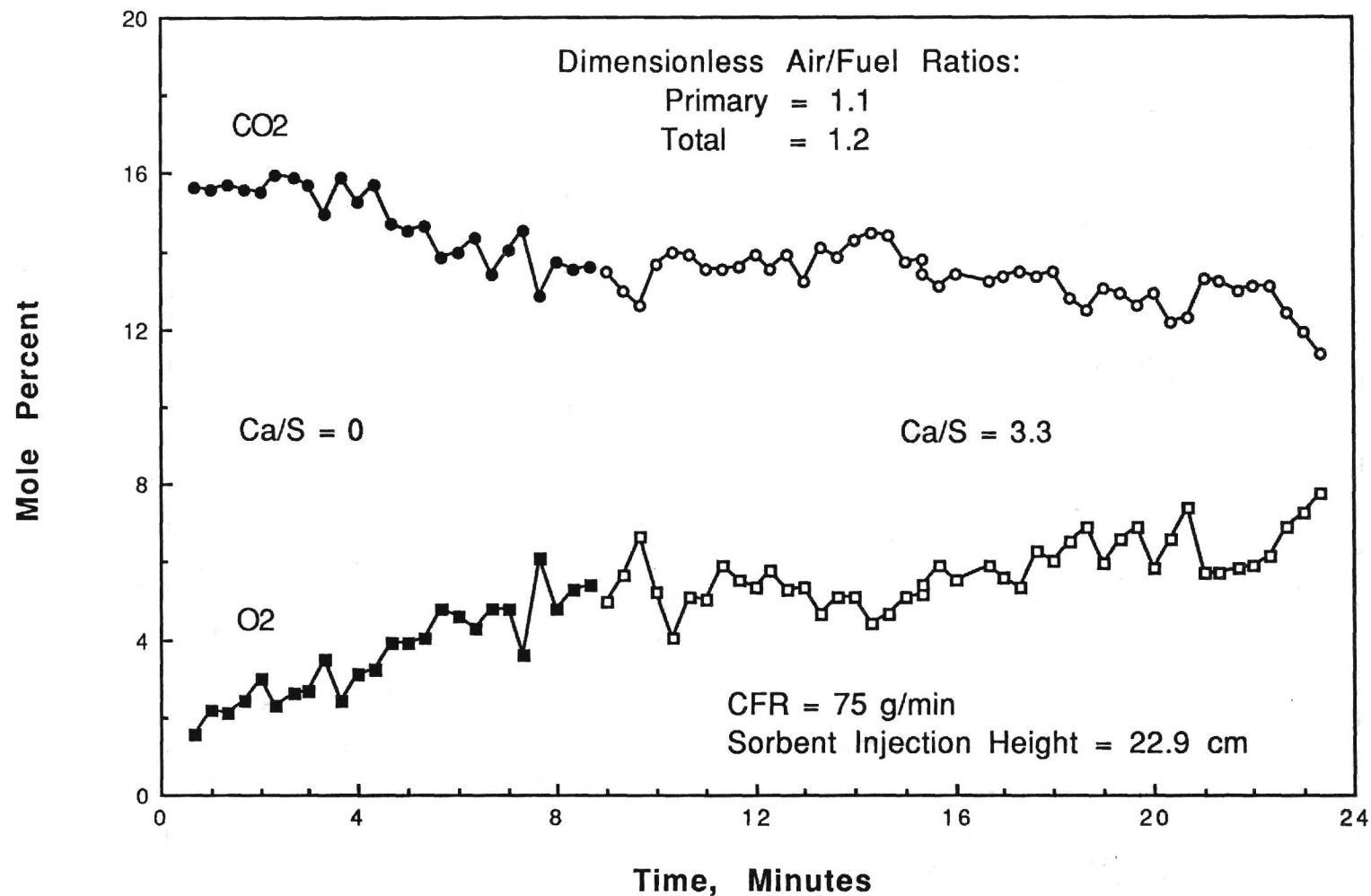


Figure 43. Real Time Carbon Dioxide and Oxygen Concentrations for a Typical Experiment with Pulverized Dolomitic Limestone Injection Above Bed.

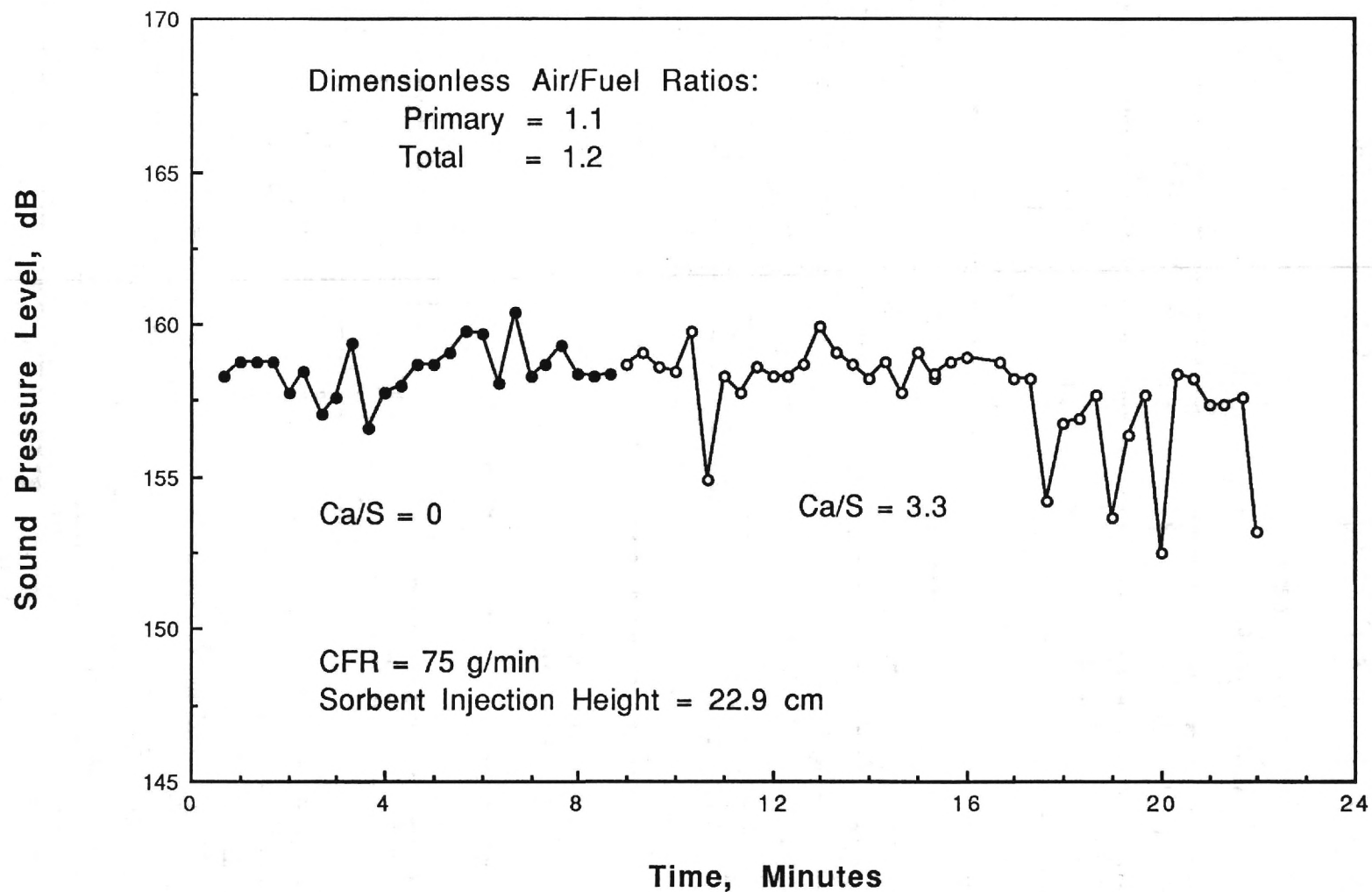


Figure 44. Real Time Sound Pressure Levels for a Typical Experiment with Pulverized Dolomitic Limestone Injection Above Bed.

sound pressure levels (SPL), and gas temperatures at 15 cm above the bed ( $T_2$ ) for sorbent injection at 15 cm above the bed. Table IX gives the same data for sorbent injection at 23 cm above the bed.

Table VIII. Results of Sorbent Addition Experiments with Injection Height of 15 cm.

Run No.	Ca/S	$\alpha_1$	$\alpha_t$	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)	CO <sub>2</sub> (ppm)	SPL (dB)	T <sub>2</sub> (C)
3	0.0	1.1	1.2	894	6.45	12.01	155.0	1058
3	6.0	1.1	1.2	628	6.60	12.25	151.6	1076
4	0.0	1.1	1.2	1078	4.62	14.60	158.0	1132
4	4.0	1.1	1.2	654	5.90	14.31	156.8	1144
5	0.0	1.1	1.2	720	5.83	11.86	158.6	1040
6	0.0	1.1	1.2	945	5.37	14.42	158.9	1086
10	4.0	1.0	1.1	490	6.23	12.58	157.8	1035
10	5.5	1.0	1.1	298	6.90	12.01	157.6	1042
10	6.5	1.0	1.1	260	6.57	12.38	157.3	1058
11	0.0	1.0	1.2	900	5.50	12.98	157.6	1055
11	4.0	1.0	1.2	287	7.17	11.79	156.8	1015
12	1.8	1.0	1.1	402	6.39	12.59	156.9	987
13	2.4	1.1	1.05	155	5.82	13.48	156.0	1017

Table IX. Results of Sorbent Addition Experiments with Injection Height of 23 cm.

Run No.	Ca/S	$\alpha_1$	$\alpha_t$	SO <sub>2</sub> (ppm)	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	SPL (dB)	T <sub>2</sub> (C)
1	0.0	1.1	1.3	1235	4.55	13.29	157.9	1091
1	6.0	1.1	1.3	998	7.39	11.02	158.0	1079
1	8.0	1.1	1.3	944	7.35	11.12	158.0	1078
2	0.0	1.1	1.3	1123	5.85	12.14	158.0	1077
2	6.0	1.1	1.3	548	6.63	11.97	157.4	1089
2	8.0	1.1	1.3	280	5.47	13.70	156.9	1135
7	0.0	1.0	1.2	859	4.40	14.21	158.7	1091
7	3.3	1.1	1.2	299	6.15	12.96	153.8	1109
8	3.3	1.0	1.1	572	5.67	14.77	157.1	1125
9	3.3	1.0	1.2	622	6.76	9.74	151.1	1023

Inspection of Tables VIII and IX reveals considerable variation in measured species concentrations for similar conditions. For example, exhaust SO<sub>2</sub> concentrations ranged from about 720 ppm to 1240 ppm for operation without limestone injection, and for limestone injection at 15 cm above the bed with a Ca/S ratio of 4.0, SO<sub>2</sub> concentrations varied from 290 ppm to 650 ppm. At an injection height of 23 cm and a Ca/S ratio of 3.3, SO<sub>2</sub> concentrations ranged from about 300 ppm to 620 ppm. It is unlikely that these variations are caused by the differences in the primary and total dimensionless air/fuel ratios ( $\alpha_1$  and  $\alpha_t$ ) for these experiments. It is more likely that some other factors, such as sorbent particle size distribution and gas temperature, which are difficult to control in these experiments, are causing these variations in SO<sub>2</sub> emissions. Carbon dioxide and oxygen concentrations exhibited smaller but significant variations, indicating variations in combustion efficiency. Over all of the experiments, CO<sub>2</sub> concentrations ranged between 9.7 and 14.8 percent, while O<sub>2</sub> concentrations varied from 4.4 to 7.4 percent. Sound pressure levels ranged from about 150 dB (case with lowest CO<sub>2</sub> concentration) to about 159 dB. Gas temperatures at 15 cm above the bed varied from about 990 C to about 1140 C.

The effect of Ca/S mole ratio on sulfur dioxide concentrations for this series of experiments is shown in Figure 45 for sorbent injection at 15 cm above the bed and in Figure 46 for a sorbent injection height of 23 cm. For the lower injection height (Figure 45), sorbent injection consistently resulted in lower SO<sub>2</sub> emissions than the baseline average of about 910 ppm, with the lowest emissions being obtained for the five experiments conducted with  $\alpha_1 = 1.0$  and  $\alpha_t = 1.1$ . Only for this case, was there sufficient data to show a mild trend of decreasing SO<sub>2</sub> emissions with increasing Ca/S ratio. The greatest reduction in SO<sub>2</sub> concentration of about 83 percent occurred for the experiment conducted at Ca/S = 2.4 (#13). For this case and one conducted at a Ca/S ratio of 1.8 (#12), the sorbent particle size was the smallest, about 40  $\mu\text{m}$ . For the highest primary and total air/fuel ratios ( $\alpha_1 = 1.1$  and  $\alpha_t = 1.2$ ), the reductions in SO<sub>2</sub> emissions were much smaller, averaging about 35 percent. For

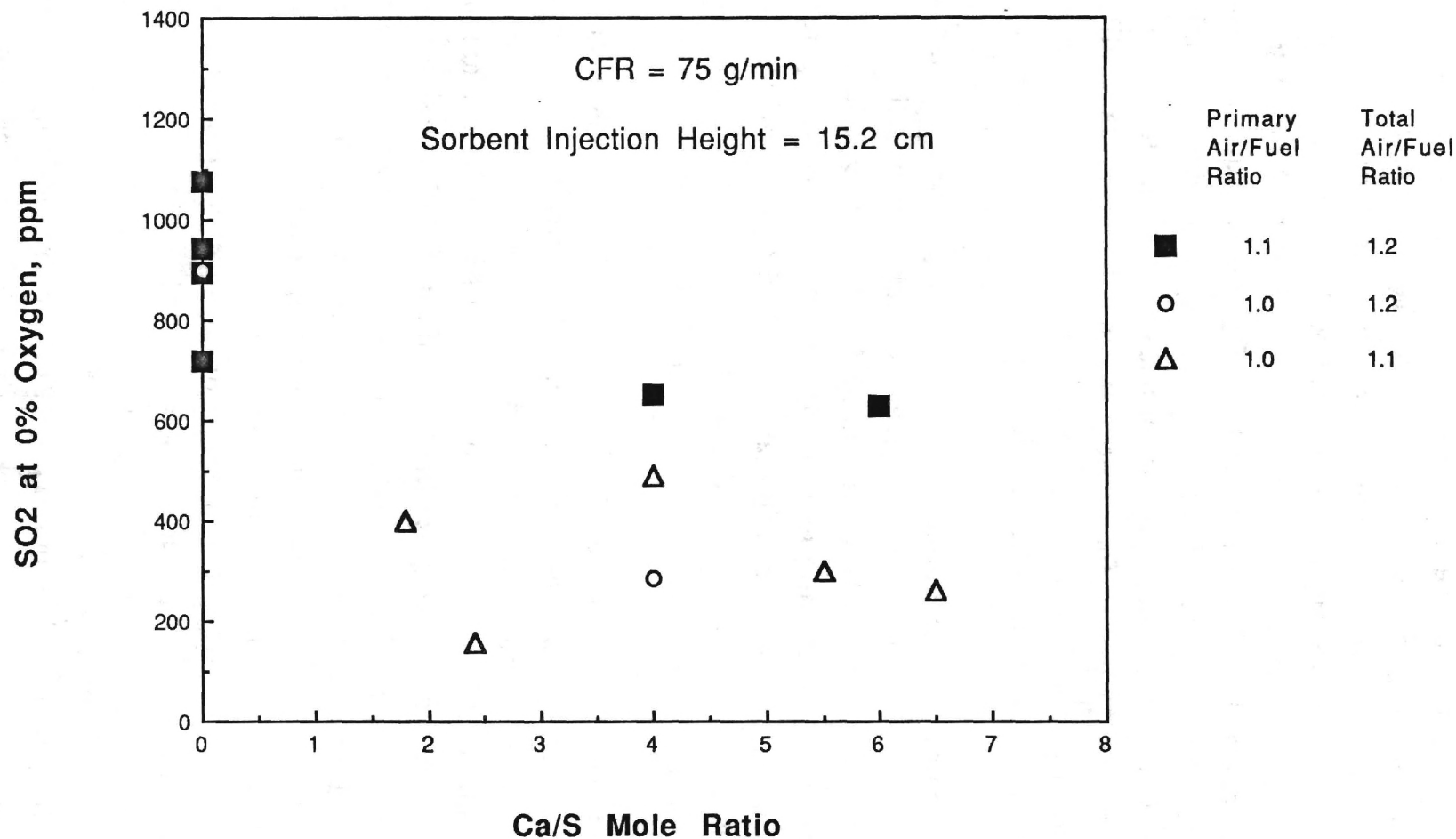


Figure 45. Effect of Ca/S Ratio upon Sulfur Dioxide Concentrations for Experiments with Pulverized Dolomitic Limestone Injection at 15 cm Above the Bed.

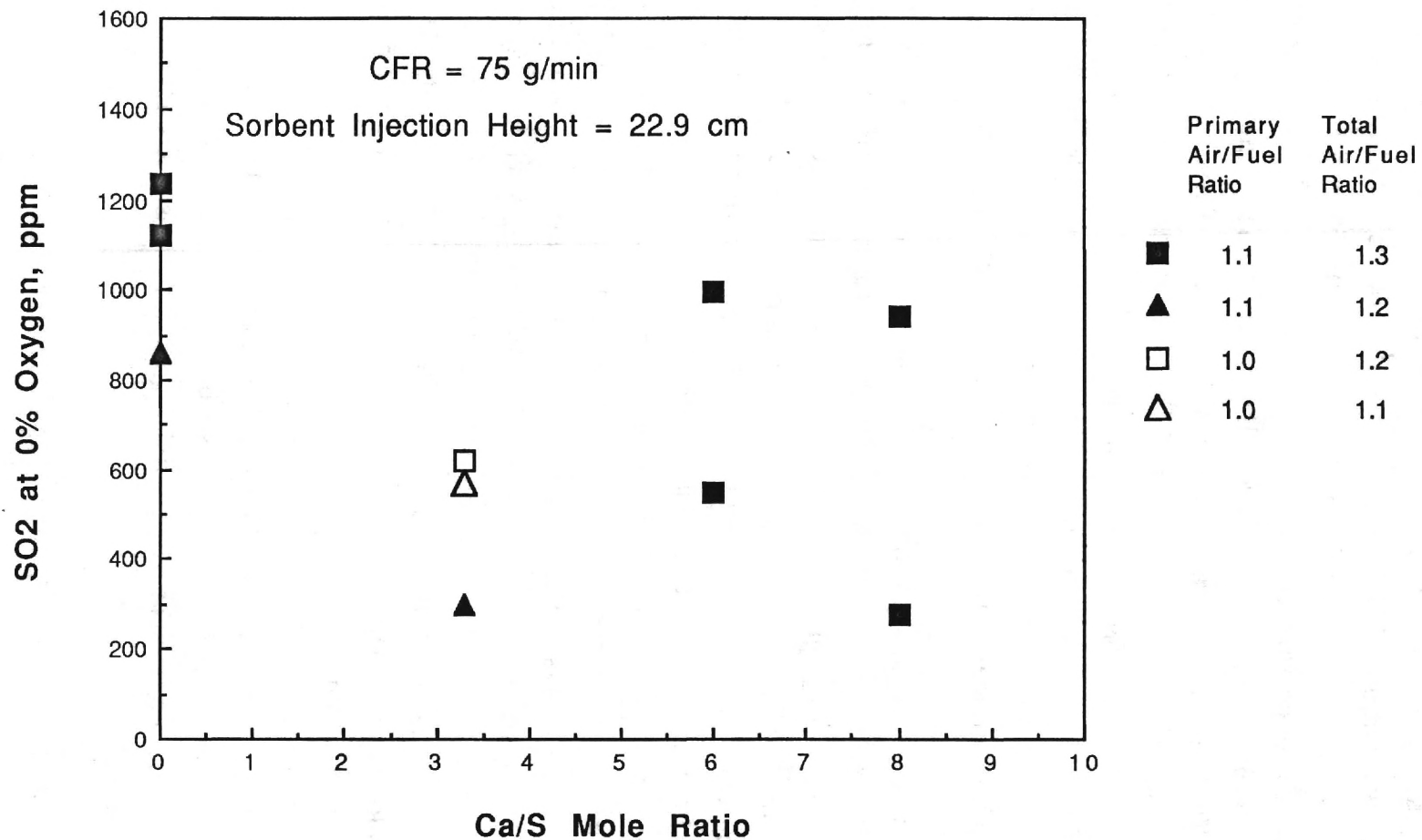


Figure 46. Effect of Ca/S Ratio upon Sulfur Dioxide Concentrations for Experiments with Pulverized Dolomitic Limestone Injection at 23 cm Above the Bed.

sorbent injection at 23 cm (Figure 46), most of the experiments were conducted with  $\alpha_1 = 1.1$  and  $\alpha_t = 1.3$ . Here the average baseline  $\text{SO}_2$  concentration was about 1180 ppm, and  $\text{SO}_2$  reductions ranged from about 20 percent (#1 at Ca/S of 6) to about 75 percent (#2 at Ca/S = 8). Three experiments with a Ca/S ratio of 3.3 and different primary and total air/fuel ratios are also shown. Here increasing the primary air/fuel ratio for a fixed total air/fuel ratio ( $\alpha_t = 1.2$ ) resulted in a significant reduction in  $\text{SO}_2$  emissions, while changing the total air/fuel ratio for a fixed primary air/fuel ratio ( $\alpha_1 = 1.0$ ) had little effect on  $\text{SO}_2$  concentration. Comparison of the data shown in Figures 45 and 46 shows no clear effect of sorbent injection height upon the exhaust concentration of  $\text{SO}_2$  for this series of experiments.

Due to the large amount of scatter in the graphs of  $\text{SO}_2$  concentration versus Ca/S ratio, additional graphs were plotted in order to correlate  $\text{SO}_2$  emission with other variables such as residual oxygen concentration and gas temperature. Since there was considerable variation in combustion efficiency among experiments for fixed primary and total air/fuel ratios, all of the  $\text{SO}_2$  concentration data were plotted as a function of residual oxygen levels in the exhaust stream. The resulting graph is shown in Figure 47, where the data has been classified into five groups according to Ca/S ratio, but no distinction is made regarding sorbent injection height. Again there is a large amount of scatter in the data, indicating that there is no significant correlation between  $\text{SO}_2$  and  $\text{O}_2$  levels. Figure 47 shows, however, that except for two cases, all of the  $\text{SO}_2$  concentrations measured with sorbent addition are lower than the  $\text{SO}_2$  concentrations obtained without sorbent addition (Ca/S = 0.0). This graph also shows that residual oxygen levels tend to be significantly higher for cases with sorbent injection, which implies that injection of the limestone particles results in somewhat reduced combustion efficiency.

To determine the effect of gas temperature on the sulfur capture process, a graph was plotted of  $\text{SO}_2$  concentration as a function of the gas temperature at a height of 15 cm above the bed.

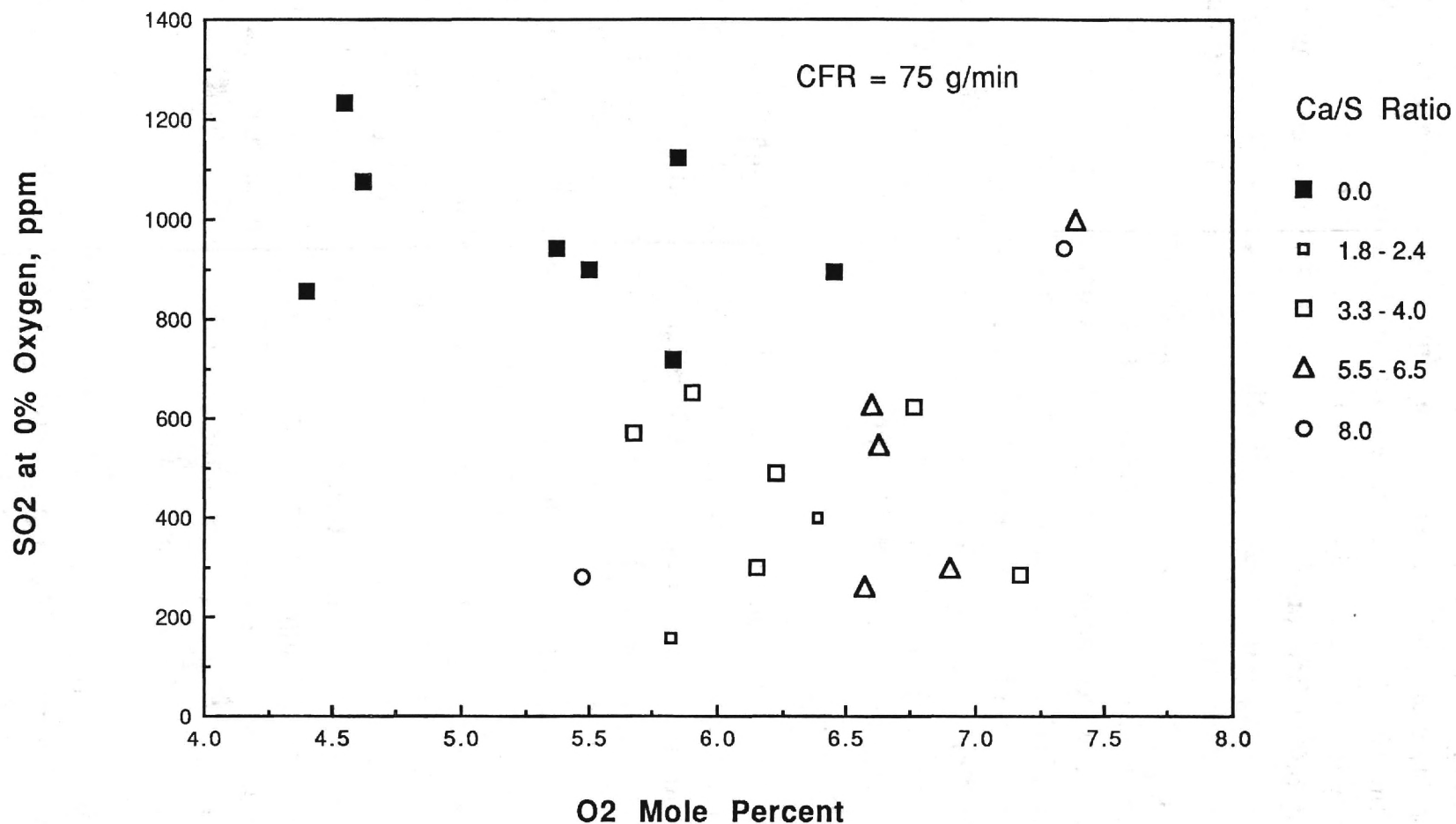


Figure 47. Correlation of Sulfur Dioxide Concentrations with Residual Oxygen Concentrations for Experiments with Pulverized Dolomitic Limestone Injection Above the Bed.

This corresponds to the temperature at the sorbent injection height for the lower injector position, and for a temperature 8 cm below the injection height for the upper injector position. Figure 48 shows this graph, again with the data classified into groups according to Ca/S ratio, but without indication of injection height. There is considerable scatter in this data, indicating no significant correlation of the SO<sub>2</sub> concentrations with the gas temperature. Although the optimum temperature for the sulfur capture process is known to be about 900 C [8], in seven cases large reductions in SO<sub>2</sub> emissions were obtained over a wide range of temperatures from just under 1000 C to nearly 1150 C. For six other cases, only moderate reductions in SO<sub>2</sub> emissions were obtained over a similar temperature range. As with the preceding figure, this graph shows, that with the exception of two cases, pulverized dolomitic limestone addition resulted in moderate to large reductions in sulfur dioxide emissions during pulsating combustion conditions.

The effect of the sorbent particles on pulsation amplitudes for these experiments is shown in Figure 49, where sound pressure levels are plotted as a function of Ca/S ratio. The plotted data points are distinguished only according to sorbent injection height. For most of these cases there is only a slight decrease in pulsation amplitude due to the damping effect of the sorbent particles. For no sorbent injection (Ca/S = 0), the average sound pressure level was 158.2 dB, excluding the lowest point. Particle damping resulted in a reduction of sound pressure level by a maximum of about 1.8 dB for Ca/S ratios of about 2, with an average loss of only about 0.6 dB for Ca/S ratios near 6. For four other cases, much larger losses in pulsation amplitude occurred, ranging from about 3 dB (Ca/S = 0) to about 7 dB. These larger losses in pulsation amplitude are probably due to other effects, such as bed nonuniformities, rather than to the damping effects of the limestone particles.

Finally, results of this study were compared with results presented in papers by Sheu, et al [8] and Wang, et al [9], who burned unpulverized coal in a similar Rijke type pulse combustor. In

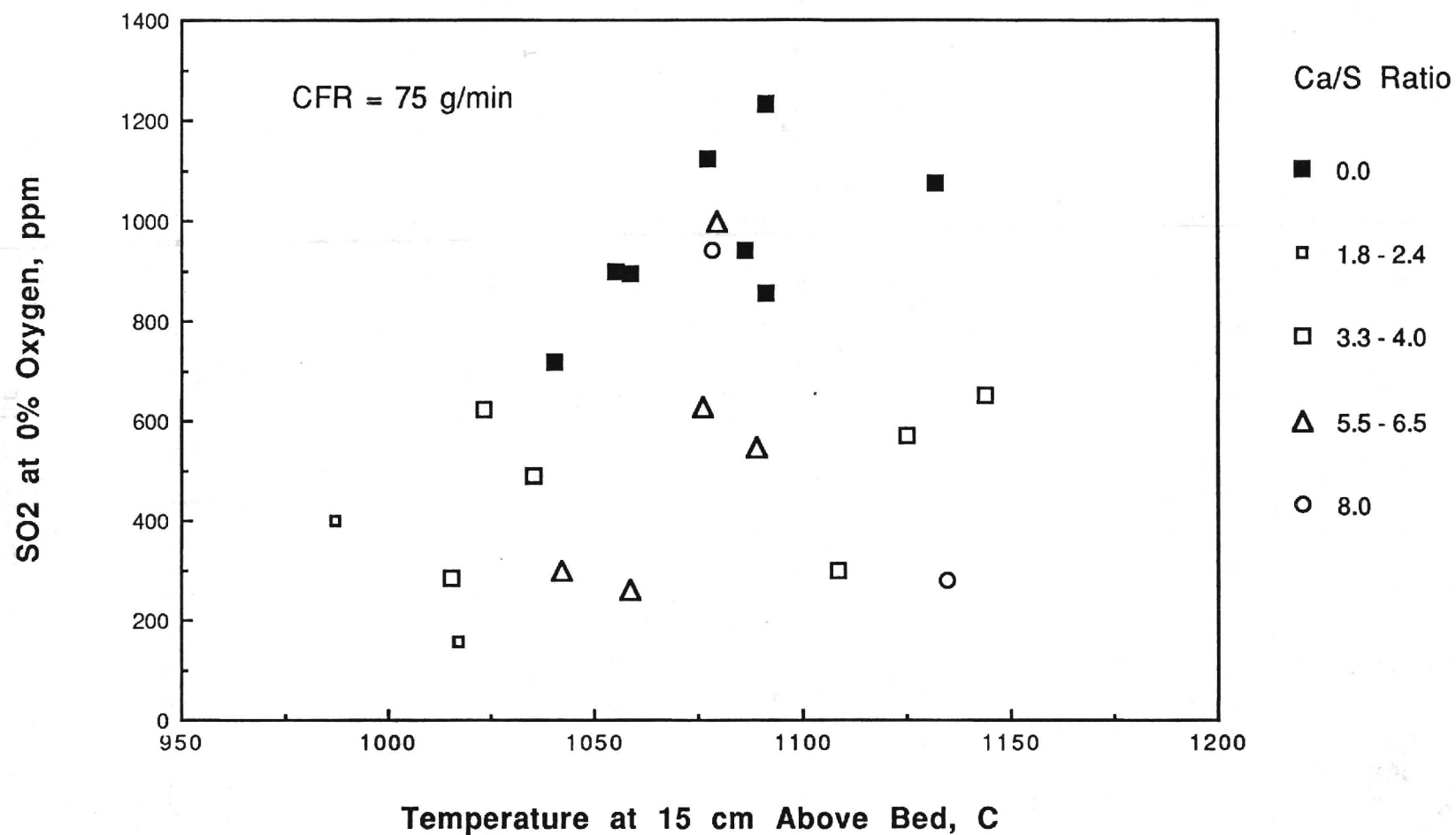


Figure 48. Correlation of Sulfur Dioxide Concentrations with Gas Temperatures for Experiments with Pulverized Dolomitic Limestone Injection Above the Bed.

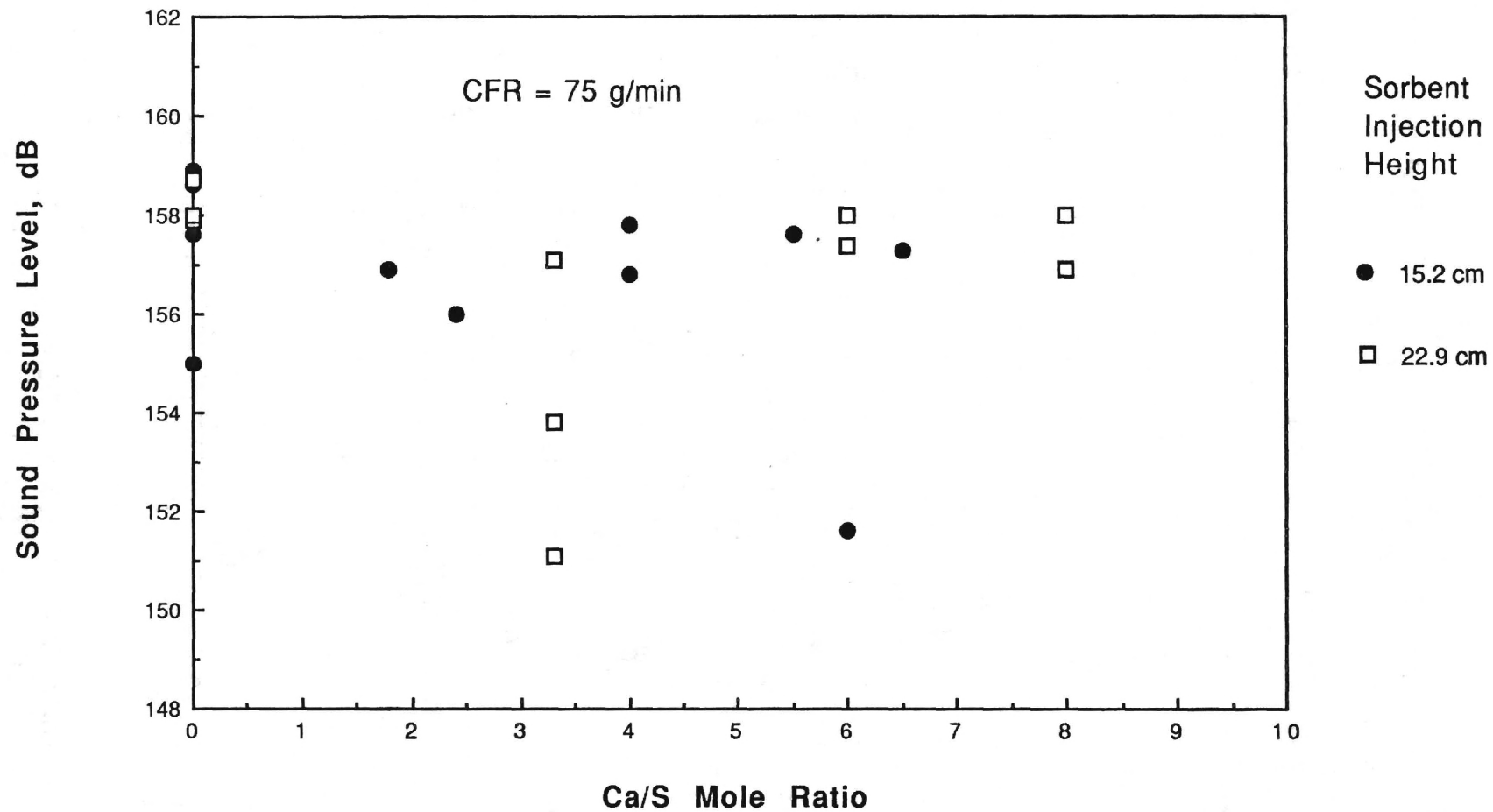


Figure 49. Effect of Sorbent Particles upon Pulsation Amplitudes for Experiments with Pulverized Dolomitic Limestone Injection Above the Bed.

their studies, Sheu and Wang added the limestone or dolomite sorbents directly to the coal bed using a motor driven auger system. Like Sheu and Wang, the results of the present investigation show that the sulfur retention by dolomitic limestone was insensitive to the amount of excess air present. For dolomite, Sheu, et al, obtained a reduction of sulfur dioxide emissions of only 17 percent for a mean particle size of 2.75 mm at a Ca/S ratio of 3.0 [8]. Sulfur retention increased with decreasing particle size at the same Ca/S ratio, reaching 83 percent SO<sub>2</sub> reduction at a mean particle size of 0.5 mm. This latter result from Sheu compares favorably with an SO<sub>2</sub> reduction of 83 percent obtained in one of the experiments of the current investigation at a Ca/S ratio of 2.4 with dolomite particles of about 40  $\mu$ m diameter. On the other hand, the results of Sheu, et al [8] indicated clear trends of increasing sulfur retention with increasing Ca/S ratio, a result which was not obtained in the present study. Also Sheu obtained maximum sulfur retention at a temperature of about 900 C, which was about 100 C lower than the lowest temperatures obtained in the present investigation. In their studies, Sheu and Wang obtained pulsation amplitudes slightly above 160 dB which agrees well with the amplitudes obtained in the current investigation.

## SUMMARY AND CONCLUSIONS

In this investigation, a Rijke pulse combustor was constructed, in which unpulverized coal is burned on a rotating bed where the presence of acoustic velocity oscillations results in bed fluidization and intensification of the combustion process. The objectives of this investigation were to determine (1) if the nitrogen oxides emissions of the experimental Rijke pulse combustor could be reduced by air staging the combustion process and (2) if the sulfur dioxide emissions of this pulse combustor could be reduced by the addition of sorbent materials such as limestone to the coal bed or to the gas stream above the bed.

A series of experiments was conducted without air staging or sorbent addition in order to determine the baseline emissions of  $\text{NO}_x$  and  $\text{SO}_2$ . A bituminous coal with about 1.5 percent nitrogen and about 1.3 percent sulfur was burned in all of the experiments. Under pulsating combustion conditions at a sound pressure level of about 160 dB and a frequency of about 65 Hz,  $\text{NO}_x$  emissions (3% oxygen basis) ranged from about 250 ppm for extremely fuel rich combustion ( $\alpha = 0.6$ ) to about 700 ppm for large excess air conditions ( $\alpha = 1.5$ ). Peak  $\text{SO}_2$  emissions of about 1400 ppm were measured at about 10 percent excess air, with minimum emissions of about 850 ppm for fuel rich combustion and somewhat less than peak emissions (about 1200 ppm) for large excess air conditions.

Two series of air staging experiments were conducted: (1) for total dimensionless air fuel ratios of 1.0 and (2) for total dimensionless air/fuel ratios ranging from 1.1 to 1.4. In both series of experiments, primary dimensionless air/fuel ratios ranged from 0.6 to 0.9. The results of this investigation showed that air staging is effective in reducing the nitrogen oxides emissions of coal burning Rijke type pulse combustors under the proper conditions. The largest reductions in  $\text{NO}_x$  emissions were obtained for primary dimensionless air/fuel ratios of about 0.7 with sufficient secondary air injection to yield total dimensionless air/fuel ratios between 1.1 and 1.4. For excess air values less than about 10 percent, air staging resulted in only small reductions in  $\text{NO}_x$  emissions. The injection point should be sufficiently high above the bed that the temperature is too low for significant thermal  $\text{NO}_x$  generation. Under these conditions  $\text{NO}_x$  emissions can be reduced by up to about 56 percent below the baseline concentrations obtained without air staging.

Two series of experiments were conducted using sorbent addition to reduce sulfur dioxide emissions. In the first series of experiments, pulverized dolomitic limestone was introduced along with the coal through the coal delivery tube just above the bed. In the second series of experiments, the dolomitic limestone was dispersed in an air stream and injected at 15 cm or 23 cm above the

coal bed. For sorbent introduced into the coal feed stream, sulfur dioxide reductions of only about 20 percent were obtained for pulsating combustion with about 20 percent excess air. For these experiments, there was a definite trend of decreasing SO<sub>2</sub> emissions with increases in excess air. Much higher SO<sub>2</sub> reductions were obtained when the sorbent was injected using the air entrainment system. There was much variation in the SO<sub>2</sub> reductions among the experiments in this series, even for the same Ca/S ratio, which was probably due to variations in combustion temperature or sorbent particle size. In many of these experiments, SO<sub>2</sub> reductions in excess of 50 percent were obtained. In one experiment, conducted at a Ca/S ratio of 2.4 with sorbent particles having a mean diameter of about 40  $\mu$ m, an SO<sub>2</sub> reduction of 83 percent was obtained. From these experiments, it is concluded that injection of pulverized dolomitic limestone above the bed under pulsating combustion conditions can reduce sulfur dioxide emissions to acceptable levels.

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